Electrical Chemical Machining

ME688: Advanced Machining Processes
Instructor: R K Mittal

Introduction

- Electrochemical machining (ECM) is a process that relies on the principle of electrolysis for material removal
- A depleting action between a conductive workpiece and a shaped tool produces a predictable erosion of the workpiece
- ECM is opposite of electrochemical or galvanic coating or deposition process
- ECM is a controlled anodic dissolution at atomic level of the work piece
- Dissolution due to flow of high current at relatively low potential difference through an electrolyte
- Electrolyte is quite often water based neutral salt solution.

Electrolysis Principle

- Electrical energy is transported through metals by conduction of electric charges from one place to another

- Salt solutions conduct electrical energy by the migration of ions in the medium

- Faraday's law of electrolysis: The Weight of the substance produced during electrolysis process is directly proportional to the current which passes, the length of time of process and the equivalent weight of the material

- Two dissimilar metals are in contact with an electrolyte and anode loses metal to cathode
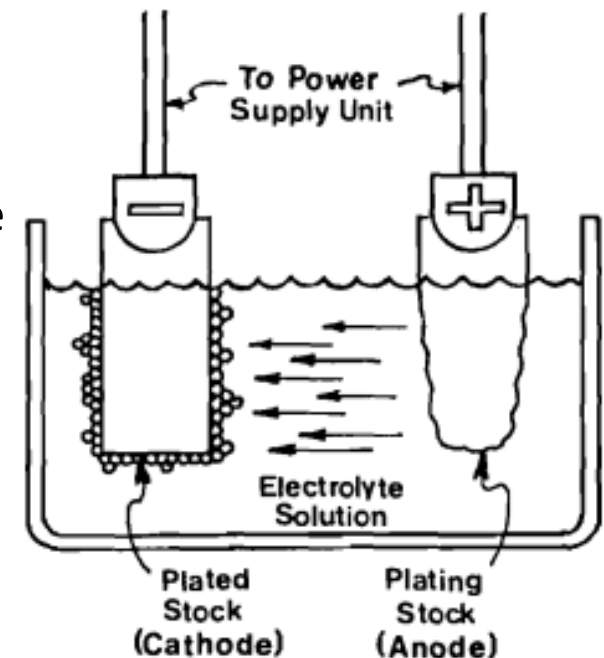
Material Removal Process

- 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

- For ECM of steel, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte

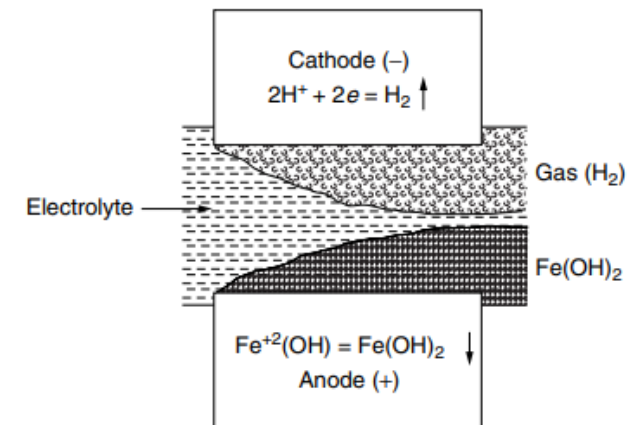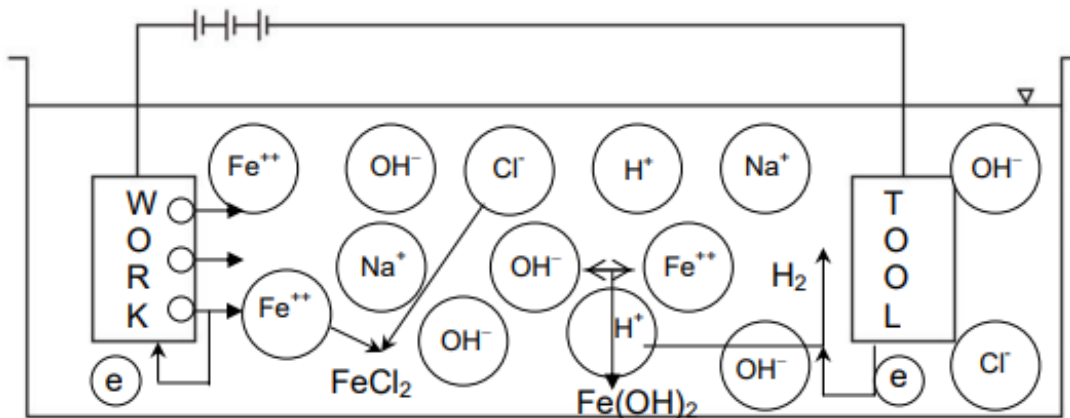- The electrolyte and water undergoes ionic dissociation as shown below as potential difference is applied

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

Material Removal Process

- 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 form hydrogen gas as:

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

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

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

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Material Removal Process

- Within the electrolyte iron ions would combine with chloride and hydroxyl ions to form $FeCl_2$ and $Fe(OH)_2$ and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide (NaOH)

- $FeCl_2$ and $Fe(OH)_2$ would form and get precipitated in the form of sludge

- There is not coating on the tool, only hydrogen gas evolves at the tool or cathode

- As the material removal takes place due to atomic level dissociation, the machined surface is of excellent surface finish and stress free.
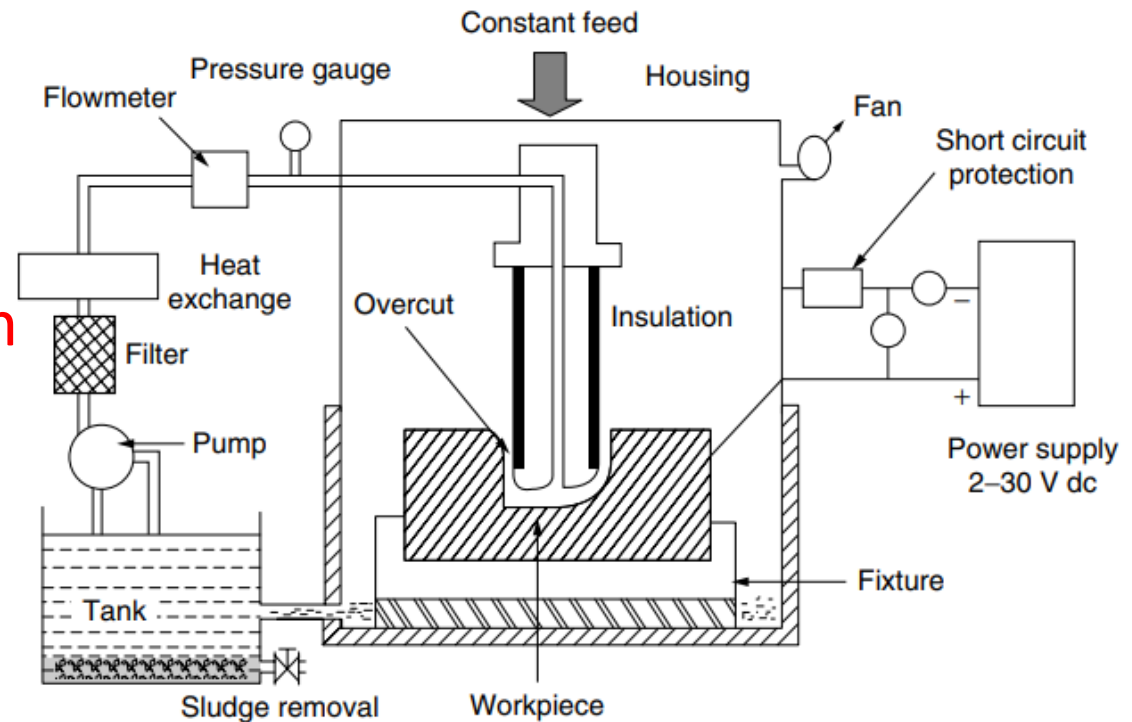
Material Removal Process
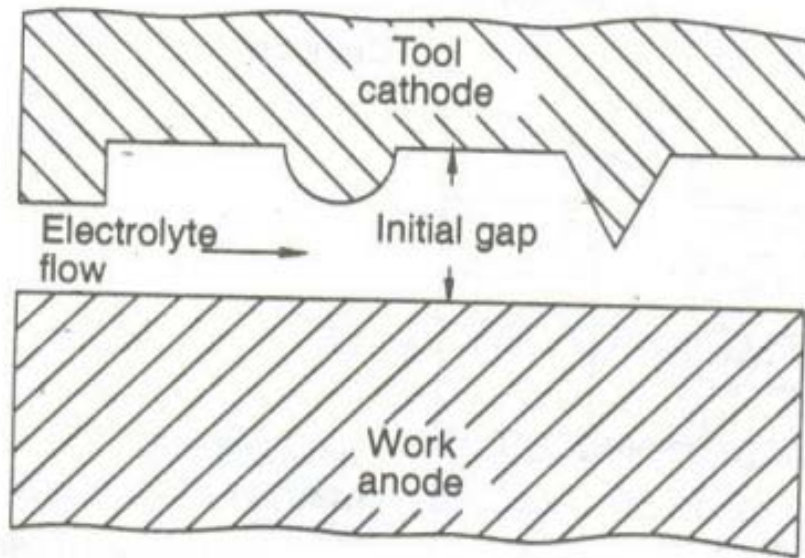
Initial position
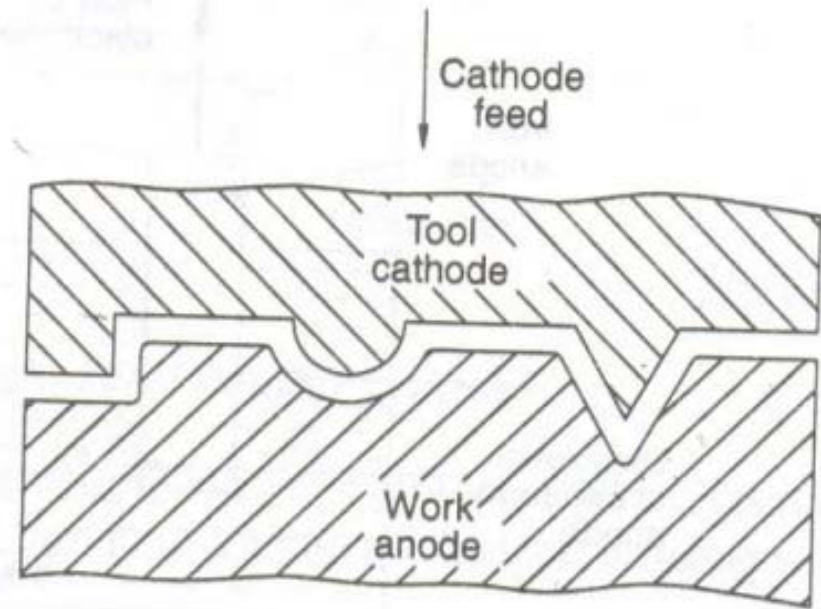
Final position

ECM System

- Power supply
- Electrolytes
- Tools
- Workpiece holding system
- Feed control system

Tool Material

- High electrical and thermal conductivity
- Good stiffness
- Easy machinability - particularly important if complex shaped tools are required
- High corrosion resistance - to protect itself from the highly corrosive electrolyte solution
- Rigidity of the tool construction and material is important because the high pressure can cause deflection of the tool
- Generally, Aluminum, Copper, Brass, Bronze, Carbon, Copper - Manganese, Copper-Tungsten, Titanium, Cupro-Nickel and Stainless Steel are used

Electrolyte

- Electrolytes are highly conductive solutions of inorganic salts, usually NaCl, KCl, and $NaNO_3$, or their mixtures to meet multiple requirements

- Complete the electric circuit between the tool and the workpiece

- Allow desirable reactions to occur and create conditions for anodic dissolution

- Carry away heat generated during chemical reactions

- Remove products of reaction (sludge) from the machining gap

- High electrical conductivity to ensure high current density

Electrolyte

- Low viscosity to ensure good flow conditions in the extremely narrow interelectrode gap
- High specific heat and thermal conductivity to be capable of removing the heat generated from the gap
- Resistance to the formation of a passive film on the workpiece surface
- High chemical stability
- Provides high current efficiency and possesses low throwing power
- Non-toxic and non-corrosive to the machine parts
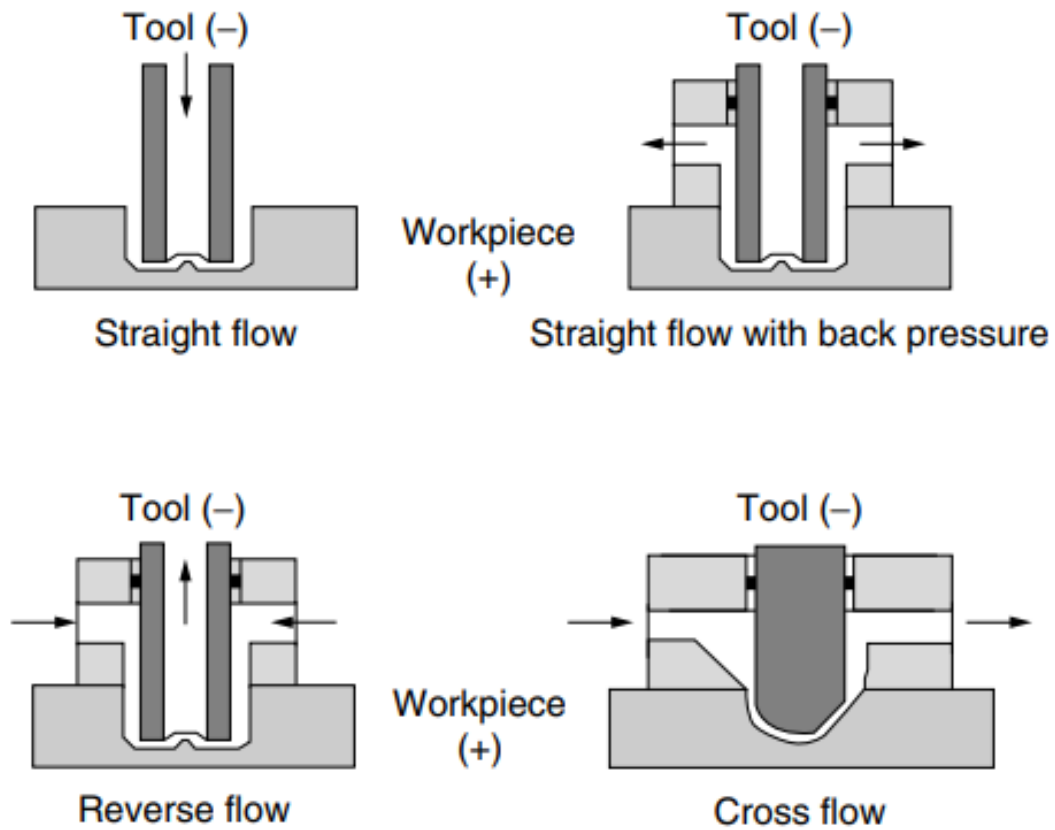- Inexpensive and available

Electrolyte
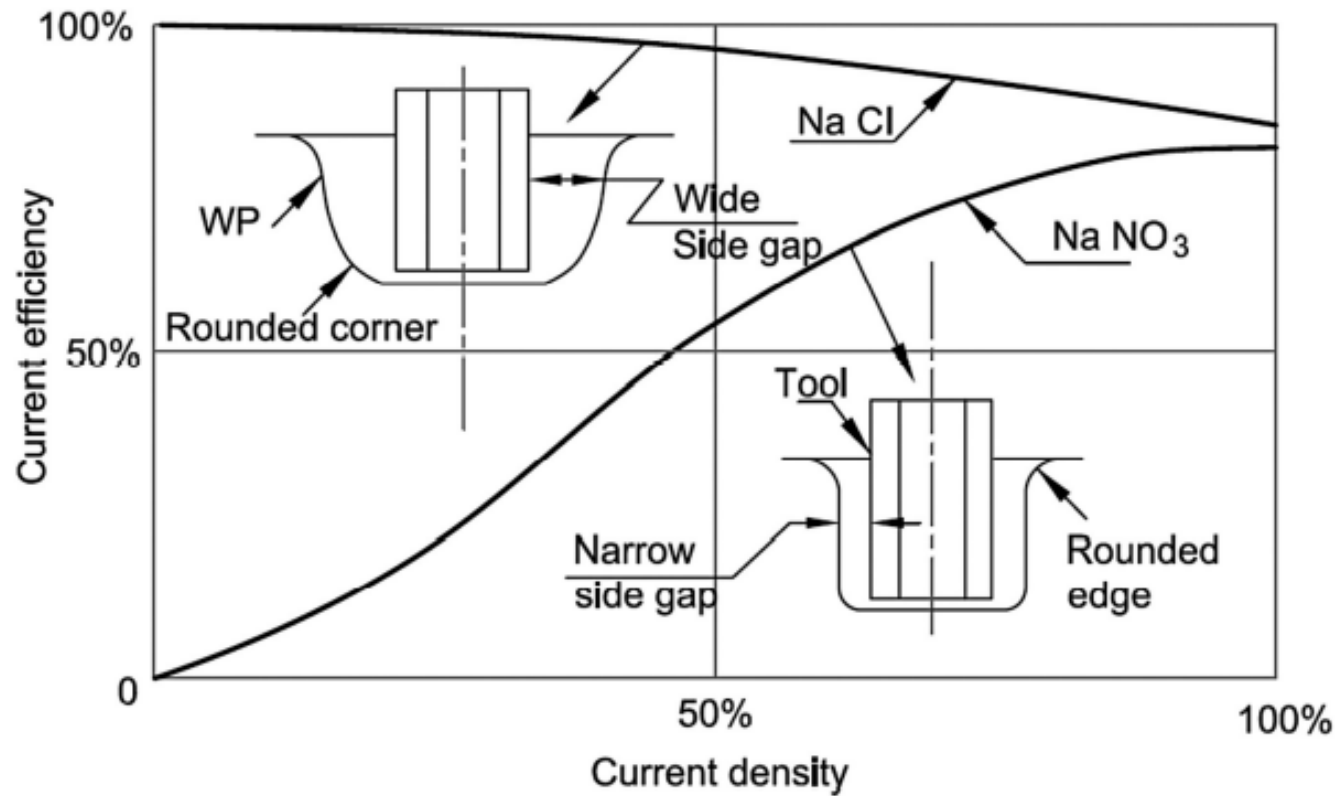
Current efficiency and side gap of NaCl and NaNO3 (Youssef, 2016)

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Electrolyte Feeding System

Straight flow

Straight flow with back pressure

Reverse flow

Cross flow

Material Removal Rate

- 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:

$$m \propto q$$

m= mass of dissolved material and q= amount of charge passes

  - 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.

$$m \propto \frac{A}{v}$$

A= atomic weight and v = valency of dissolution

Material Removal Rate

$$m \propto q \text{ and } m \propto \frac{A}{v} \quad \longrightarrow \quad m \propto \frac{qA}{v}$$

Put charge $q = \text{I} * \text{t}$

$$m = \frac{qA}{Fv} = \frac{It}{F}\frac{A}{v}$$

I= Current Strength (amperes)

t= time (seconds)

F= Faraday's constant (=96500 coulombs)

• Material removal rate:

$$MRR = \frac{m}{\rho t} = \frac{I}{F\rho}\frac{A}{v}$$

ρ=density of material

Material Removal Rate

Electrochemical Equivalent of Alloys:
- Let us assume there are 'n' elements in an alloy.
- The atomic weights are given as A_1, A_2, ..., A_n
- Valency during electrochemical dissolution as v_1, v_2, ..., v_n.
- The weight percentages of different elements are α_1, α_2, ..., α_n

First Method: percentage by weight method

$$\left(\frac{A}{v}\right)_{alloy} = \frac{1}{100}\sum_{i=1}^{n}\alpha_i\left(\frac{A_i}{v_i}\right)$$

$$MRR = \frac{I}{F\rho}\left(\frac{A}{v}\right)_{alloy} = \frac{I}{F\rho}\frac{1}{100}\sum_{i=1}^{n}\alpha_i\left(\frac{A_i}{v_i}\right)$$

Material Removal Rate

Second Method: superposition of charge method
- Each element present in the alloy takes a certain amount of charge to dissolve.

$$m_i = \frac{q_i A_i}{F v_i} \qquad \longrightarrow \qquad q_i = \frac{F m_i v_i}{A_i}$$

Total charge $q_t = It$

$$q_t = \sum_{i=1}^{n} q_i = \sum_{i=1}^{n} Fm \frac{\alpha_i}{100} \frac{v_i}{A_i}$$

$$m = \frac{It}{F \sum_{i=1}^{n} \frac{\alpha_i}{100} \frac{v_i}{A_i}}$$

$$MRR = \frac{m}{\rho t} = \frac{I}{\rho F \sum_{i=1}^{n} \frac{\alpha_i}{100} \frac{v_i}{A_i}}$$

Dynamics of Electrochemical Machining

- It is always desirable to have minimum possible gap (usually < 0.5 mm) between the two electrodes (tool and workpiece) mainly to get accurate reproduction of tool shape on the workpiece.

- Assumption:
  - Electrical conductivity (k) of electrolyte in the IEG remains constant
  - Electrical conductivities of tool and work materials are very large as compared to that of electrolyte Hence, surfaces of the electrodes can be considered as equipotentials
  - Effective voltage working across the electrodes will remain constant
  - The anode dissolves at one fixed valency of dissolution

Dynamics of Electrochemical Machining
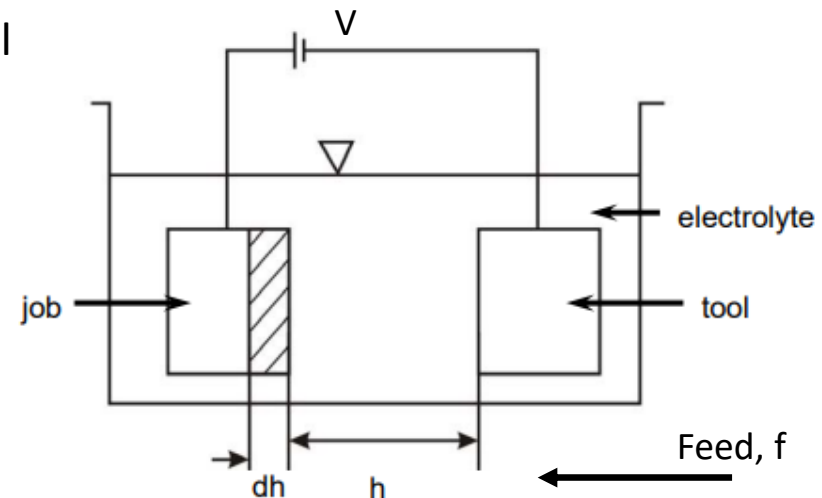
$$MRR = \frac{I}{F\rho}\frac{A}{v}$$

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

$$I = \frac{V}{R} \qquad \left(R = \frac{h}{kS}\right)$$

k= electrical conductivity (inverse proportional of resistivity)

S= area of electrode

$$I = \frac{VkS}{h}$$

V

electrolyte

job

tool

dh   h

Feed, f

Dynamics of Electrochemical Machining

$$MRR = \frac{Volume}{sec} = S\frac{dh}{dt}$$

$$MRR = S\frac{dh}{dt} = \frac{I}{F\rho}\frac{A}{v}$$

$$S\frac{dh}{dt} = \frac{VkS}{F\rho h}\frac{A}{v}$$

$$\frac{dh}{dt} = \frac{Vk}{F\rho}\frac{A}{v}\frac{1}{h} = \frac{c}{h} \qquad \left(c = \frac{Vk}{F\rho}\frac{A}{v}\right)$$

Dynamics of Electrochemical Machining

During actual ECM, tool is usually moved towards the workpiece at a feed of 'f' units/s. Hence, effective rate of change of gap is given by

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

Under equilibrium conditions,

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

$$f = \frac{c}{h_e} \quad \text{where} \left(c = \frac{Vk}{F\rho} \frac{A}{v} \right)$$

Equilibrium interelectrode gap (h_e):

$$h_e = \frac{Vk}{fF\rho} \frac{A}{v}$$

Dynamics of Electrochemical Machining

Basic differential equation of the system (rate of change of gap) is given by

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

Case 1: feed $f = 0$

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

$$h\,dh = c\,dt$$

Integrating both side

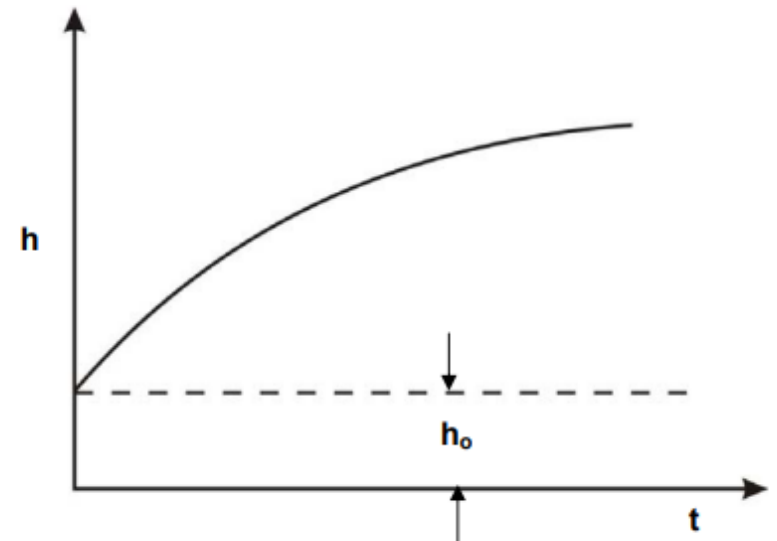$$h^2 = 2ct + K$$

At t=0, h=h_0

$$h^2 = 2ct + h_0^2$$

Dynamics of Electrochemical Machining

At t=0, h=h_0

$$h^2 = 2ct + h_0^2$$

The tool – workpiece gap under zero feed condition grows gradually

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

Dynamics of Electrochemical Machining

Case 2: finite feed ($f \neq 0$)

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

Under equilibrium conditions,

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

$$h_e = \frac{c}{f}$$

To generalized the analysis, use dimensionless parameter

$$h' = \frac{h}{h_e} = \frac{hf}{c} \ \ and \ \ t' = \frac{t}{h_e/f} = \frac{tf^2}{c}$$

Here, h' indicates the ratio of the gap to the equilibrium gap, and t' indicates the number of times required to machine one 'h_e' distance

Dynamics of Electrochemical Machining

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

In terms of h' and t',

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

Or

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

After integration,

$$t' = -h' - \ln(h' - 1) + K$$

Initial condition $t' = 0 \quad h' = h'_0 \quad K = h'_0 + \ln(h'_0 - 1)$
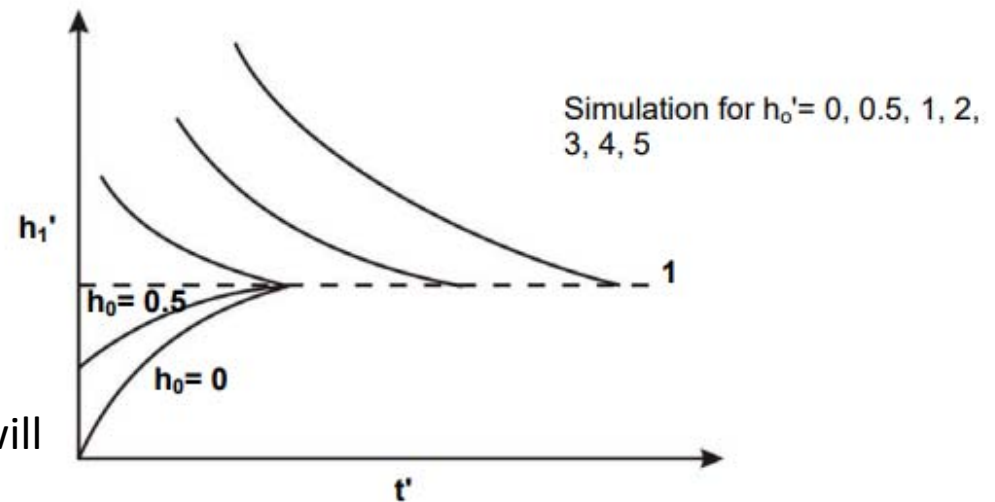
$$t' = h'_0 - h' + \ln \frac{(h'_0 - 1)}{(h' - 1)}$$

Dynamics of Electrochemical Machining

Self-regulating feature of the ECM process,

$$h' = \frac{hf}{c} = 1$$

$$f = \frac{c}{h} = \frac{Vk}{F\rho}\frac{A}{v}\frac{1}{h} = \text{MRR1} \left(\frac{\text{mm}}{\text{sec}}\right)$$

- MRR is equal to feed Thus it seems from the above equation that ECM is self regulating as MRR is equal to feed rate.
- Stable machining will take place and IEG will be equal to the equilibrium gap

Simulation for $h_o' = 0, 0.5, 1, 2, 3, 4, 5$

Variation in steady state gap with time for different initial gap

Dynamics of Electrochemical Machining

If f < MRR1,

- Initially the gap will increase and it will attain a value greater than the equilibrium gap value.

- Because of this, current density will decrease as compared to the current density at the time when the gap is equal to the equilibrium gap.

- As a result, MRR1, will also decrease. Or the difference between f and MRR1, will decrease. Finally, the IEG will start decreasing and it will attempt to attain the equilibrium gap (MRR1 = f)

Dynamics of Electrochemical Machining

If f > MRR1,

- Initially the gap will be smaller than the equilibrium gap
- As a result, current density will increase as compared to the situation when h = he, hence MRR1, will also increase.
- In other words, the difference between f and MRR1, will decrease.
- Finally, the gap will tend to attain the equilibrium gap (or MRR1 = f) value.

Maximum Permissible feed rate in ECM

$$MRR = \frac{I}{F\rho}\frac{A}{v}$$

$$I = \frac{VkS}{h}$$

Electrode feed rate is given by

$$f = \frac{MRR}{S} = \frac{I}{F\rho S}\frac{A}{v} = \frac{1}{F\rho}\frac{A}{v}\frac{Vk}{h}$$

Maximum Permissible feed rate in ECM

Using the law of conservation of heat, heat (H_0) required to raise the electrolyte temperature from T_i (temperature at inlet) to T_b (electrolyte boiling temperature can be evaluated as:

$$H_0 = m_e C_e (T_b - T_i)$$

where, m_e is the mass of electrolyte and C_e is the specific heat of electrolyte.

$$\frac{H_0}{t} = \frac{V_e}{t} \rho_e C_e (T_b - T_i)$$

where, V_e is the volume of electrolyte flowing in time t and ρ_e is the density of electrolyte.

Maximum Permissible feed rate in ECM

Power (P) required for its heating is given by (1 Cal = 4.186 Joules) :

$$P = 4.186 \, q\rho_e C_e (T_b - T_i)$$

where, q is the volumetric flow rate of electrolyte

$$P = I_m^2 R = 4.186 \, q\rho_e C_e (T_b - T_i)$$

where, I_m is the permissible maximum current and R (=h/kS) is the gap resistance.

$$I_m = \sqrt{\frac{4.186 \, q\rho_e C_e (T_b - T_i)kS}{h}}$$

Maximum Permissible feed rate in ECM

$$f = \frac{MRR}{S} = \frac{I}{F\rho S}\frac{A}{v}$$

Maximum permissible feed rate (f_m) can be calculated as:
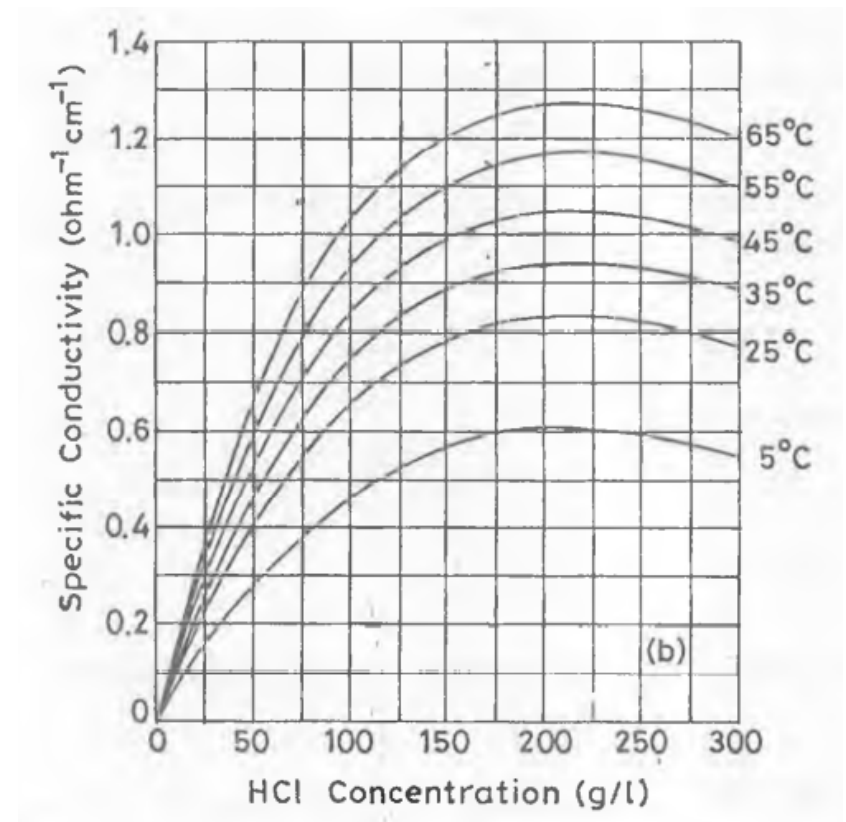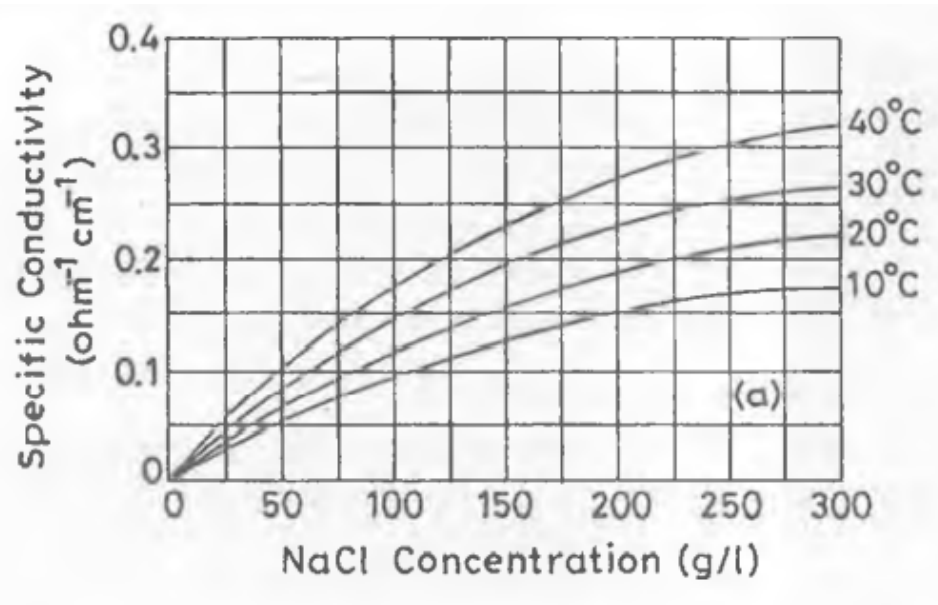
$$f_m = \frac{I_m}{F\rho S}\frac{A}{v}$$

$$f_m = \frac{1}{F\rho}\frac{A}{v}\sqrt{\frac{4.186\ q\rho_e C_e(T_b - T_i)k}{hS}}$$

Change in temperature ($\Delta T = T_b - T_i$) for the specified feed rate (f):

$$\Delta T = \frac{hS}{4.186kq\rho_e C_e}\left(\frac{fF\rho}{\frac{A}{v}}\right)^2$$

Effect of Temperature on Electrolyte Conductivity (k)

Effect of Electrolyte Conductivity (k)

- Using the law of conservation of heat, temperature gradient along the path of electrolyte flow can be derived as follows:
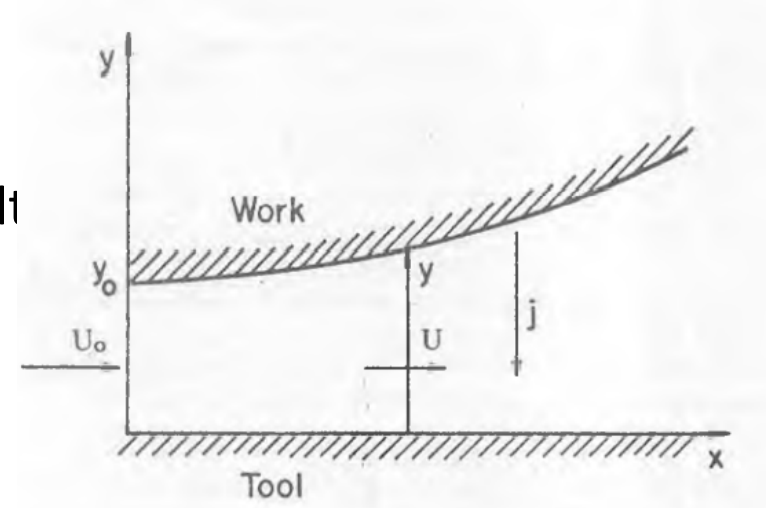
$$I^2 R = U\rho_e C_e(\Delta T)wh$$

where, U is electrolyte flow velocity, w is the width of tool

$$\frac{V^2}{R} = U\rho_e C_e(\Delta T)wh$$

Put R =h/k w dx)

$$\frac{V^2}{h} kw\, dx = U\rho_e C_e(\Delta T)wh$$

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Effect of Electrolyte Conductivity (k)

$$\frac{V^2}{h} kw \, dx = U\rho_e C_e (\Delta T) wh$$

$$\frac{dT}{dx} = \frac{V^2}{U\rho_e C_e h^2} k$$

Assume Gap and electrolyte flow velocity at inlet (h_0 and U_0) to be constant. Then, initial temperature distribution in a plane parallel gap of thickness h_0 is given by

$$\frac{dT}{dx} = \frac{V^2}{U_o \rho_e C_e h_0^2} k = L \, k \quad \left(L = \frac{V^2}{U_o \rho_e C_e h_0^2} \right)$$

Conductivity of the electrolyte varies linearly with temperature

$$k = k_0 (1 + \alpha(T - T_0))$$

Effect of Electrolyte Conductivity (k)

$$\frac{dT}{dx} = L\, k_0 (1 + \alpha(T - T_0))$$

$$\frac{dT}{(1 + \alpha(T - T_0))} = L\, k_0\, dx$$

Integrating both side,

$$ln(1 + \alpha(T - T_0)) = \alpha L\, k_0\, x$$

$$T - T_0 = \frac{1}{\alpha} e^{\alpha L\, k_0\, x} - 1$$

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Effect of Electrolyte Conductivity (k)
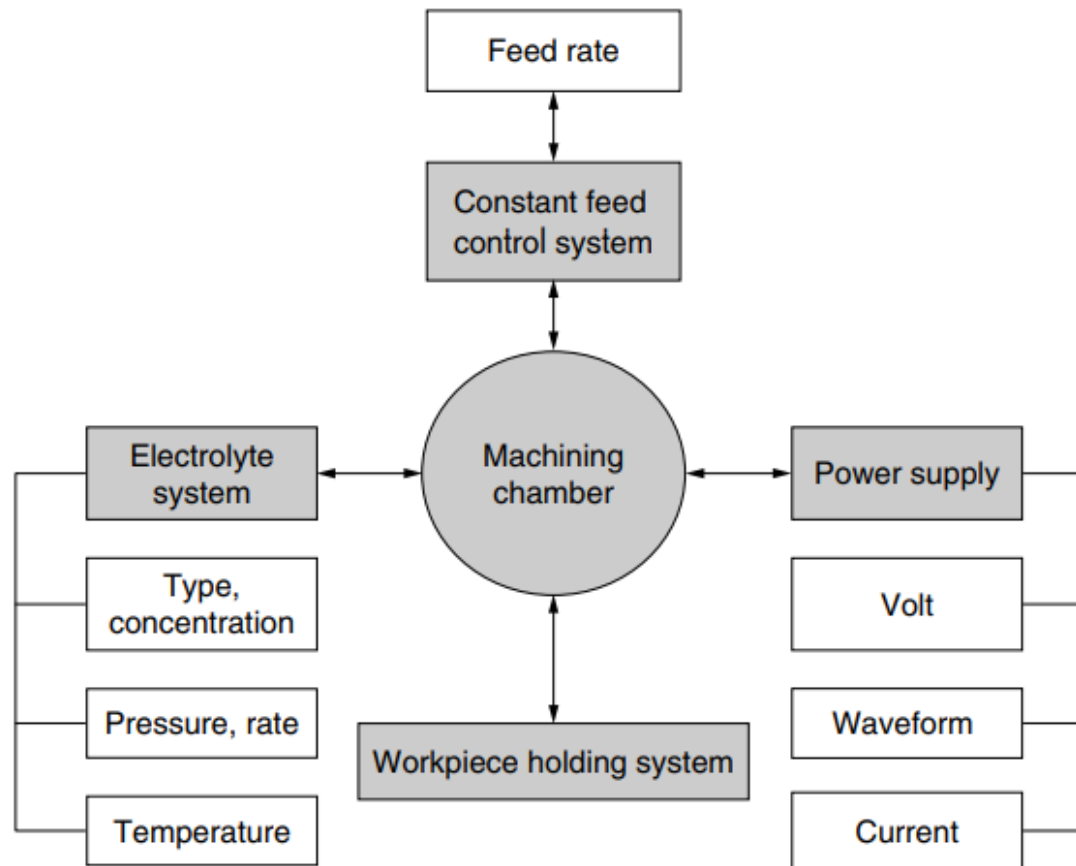
$$T - T_0 = \frac{1}{\alpha} e^{\alpha L \, k_0 x} - 1$$

The current density, J=I/S also varies along the gap and can be calculated as follows:

$$J = \frac{V}{h} k = \frac{V}{h} k_0 (1 + \alpha(T - T_0))$$

$$J = \frac{V}{h} k_0 \left(e^{\alpha L \, k_0 x} \right)$$

ECM Components

Advantage

- Three-dimensional surfaces with complicated profiles can be easily machined in a single operation irrespective of the hardness and strength of the workpiece material

- ECM offers a higher rate of metal removal as compared to traditional and nontraditional methods, especially when high machining currents are employed

- There is no wear of the tool which permits repeatable production

- No thermal damage or heat affected zone (HAZ)

- High surface quality and accuracy can be achieved at the highest MRR (R = 0.1–1.2 µm)

- Labor requirements are low

- The surfaces produced by ECM are burr-free and free from stresses

Disadvantage

- Non-conductive materials cannot be machined

- Inability to machine sharp interior corners or exterior edges of less than 0.2 mm radius

- The machine and its accessories are subjected to corrosion and rust, especially when NaCl electrolyte is used. Less corrosive but more expensive electrolytes like $NaNO_3$ can also be used

- The endurance limit of parts produced by ECM is lowered by about 10 to 25%. In such a case shot peening is recommended to restore the fatigue strength

- Metal removal rates are slow compared to traditional methods

Disadvantage

- Specific power consumption of ECM is considerably higher than that required for traditional machining
- Cavitation channels may form which deteriorates the surface quality
- Pumping electrolyte at high pressures into the narrow gap gives rise to large hydrostatic forces acting on the tool and workpiece, which necessitates rigid machine frame
- The machined parts need to be cleaned and oiled immediately after machining
- There is a danger of explosion if the hydrogen generated during machining is not safely disposed of
- The tool and the workpiece may be damaged if arcing is initiated due to the contamination of oxides and debris in the gap, or if the tool comes into contact with the workpiece causing short circuit
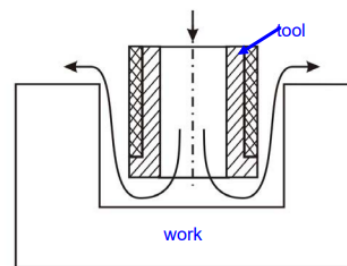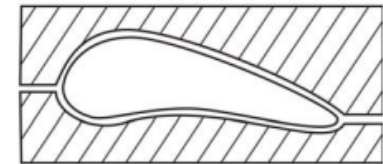
Applications

- Machining of hard materials with complex shapes
- ECM can machine any electrically conductive work material irrespective of their hardness, strength or even thermal properties.
- Die sinking
- Profiling and contouring
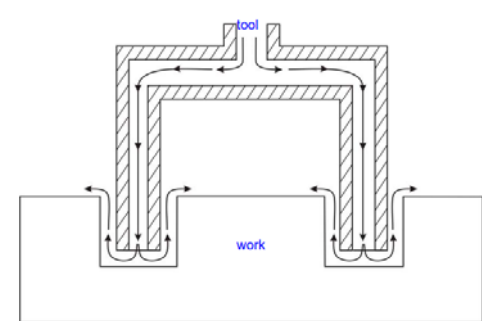- Grinding
- Drilling
- Micro-machining
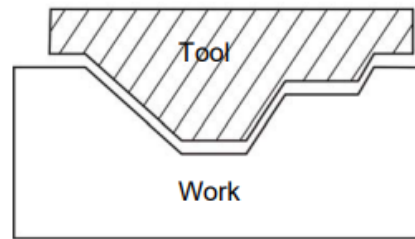
Die sinking

(drilling)

3D profiling

trepanning

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Electro Chemical Grinding

- Electrochemical grinding (ECG) is one of the most important hybrid processes, in which metal is removed by a combination of electrochemical dissolution and mechanical abrasion

- Electrochemical grinding (ECG) utilizes a negatively charged abrasive grinding wheel, electrolyte solution, and a positively charged workpiece

- The insulating abrasive material (diamond or aluminum oxide) of the grinding wheel is set in a conductive bonding material

- In ECG, the nonconducting abrasive particles act as a spacer between the wheel conductive bond and the anodic workpiece
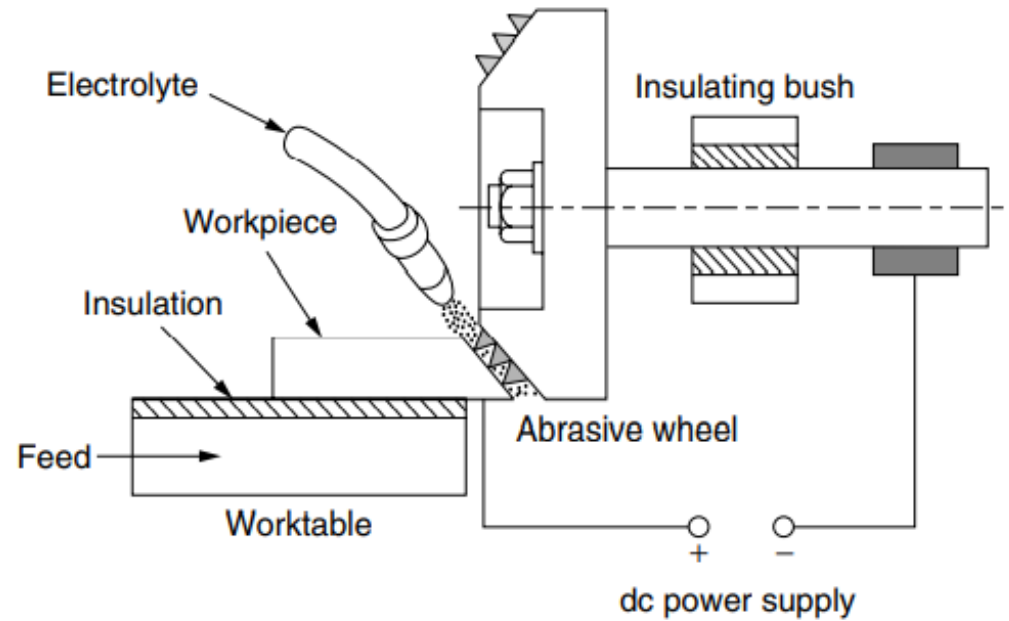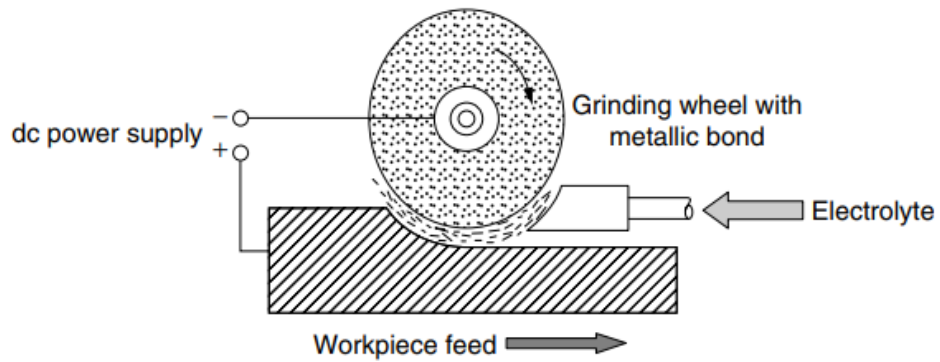
Electro Chemical Grinding

- During electrochemical grinding (ECG), material is removed by mechanical abrasive action (about 10%) and by electrochemical dissolution (about 90%) of anodic workpiece

- The commonly used electrolytes are sodium chloride (NaCl) and sodium nitrate ($NaNO_3$)

- Life o f the ECG wheel is about ten times more than that of the conventional grinding wheel

- Removal rates by ECG are four times faster than by conventional grinding, and ECG always produces burr-free parts that are unstressed

ECG Setup

Machining Zone in ECG

- In zone I material removal is purely due to electrochemical dissolution and it occurs at leading edge of the ECG wheel

- Rotation of the ECG wheel helps in drawing electrolyte into the IEG

- As a result of electrochemical reaction in zone I, reaction products (including gases) contaminate electrolyte resulting in lower conductivity

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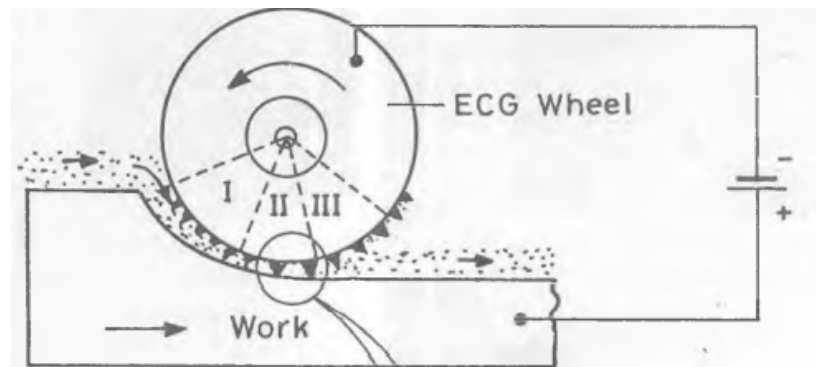
Machining Zone in ECG

- The electrolyte is being forced into the IEG in zone II by rotational motion of the wheel

- As a result, local electrolyte pressure increases in this part of the IEG (zone II)

- It suppresses formation of gas bubbles in the gap yielding higher MRR

Grinding wheel (−)   Grit

Oxide film   Metallic bond

Current lines
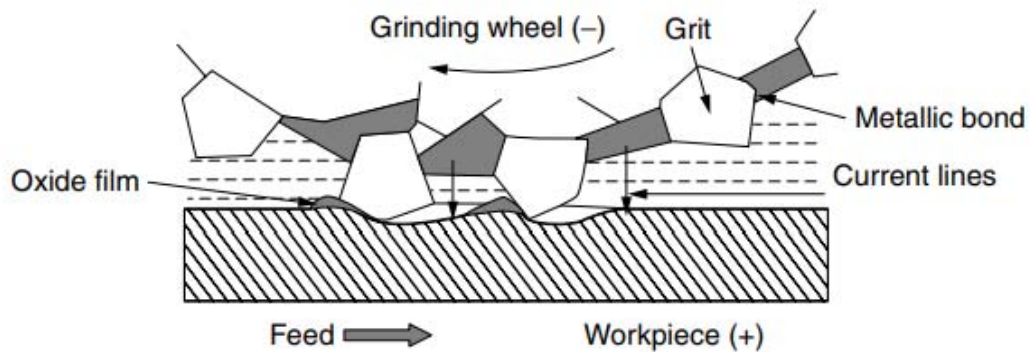
Feed   Workpiece (+)

Machining Zone in ECG

- Chemical or electrochemical reaction may result in the formation of passive layer on the workpiece-surface

- In this zone II, abrasive grains remove material from the work surface in the form of chips and also remove non-reactive oxide layer

- Most of the metal oxides formed are insoluble in water, and electrically nonconductive

- Removal of non-reactive oxide layer promotes electrolytic dissolution

- It exposes fresh metal for further electrolytic action. Hence, it is also called as "mechanical assisted electrochemical grinding" process.

Machining Zone in ECG

- In zone III, material removal is totally by electrochemical dissolution
- Zone III starts at the point where wheel lifts off the work-surface
- In this zone, pressure is released slowly
- This zone contributes to the removal of scratches or burrs that might have formed on the workpiece in zone II
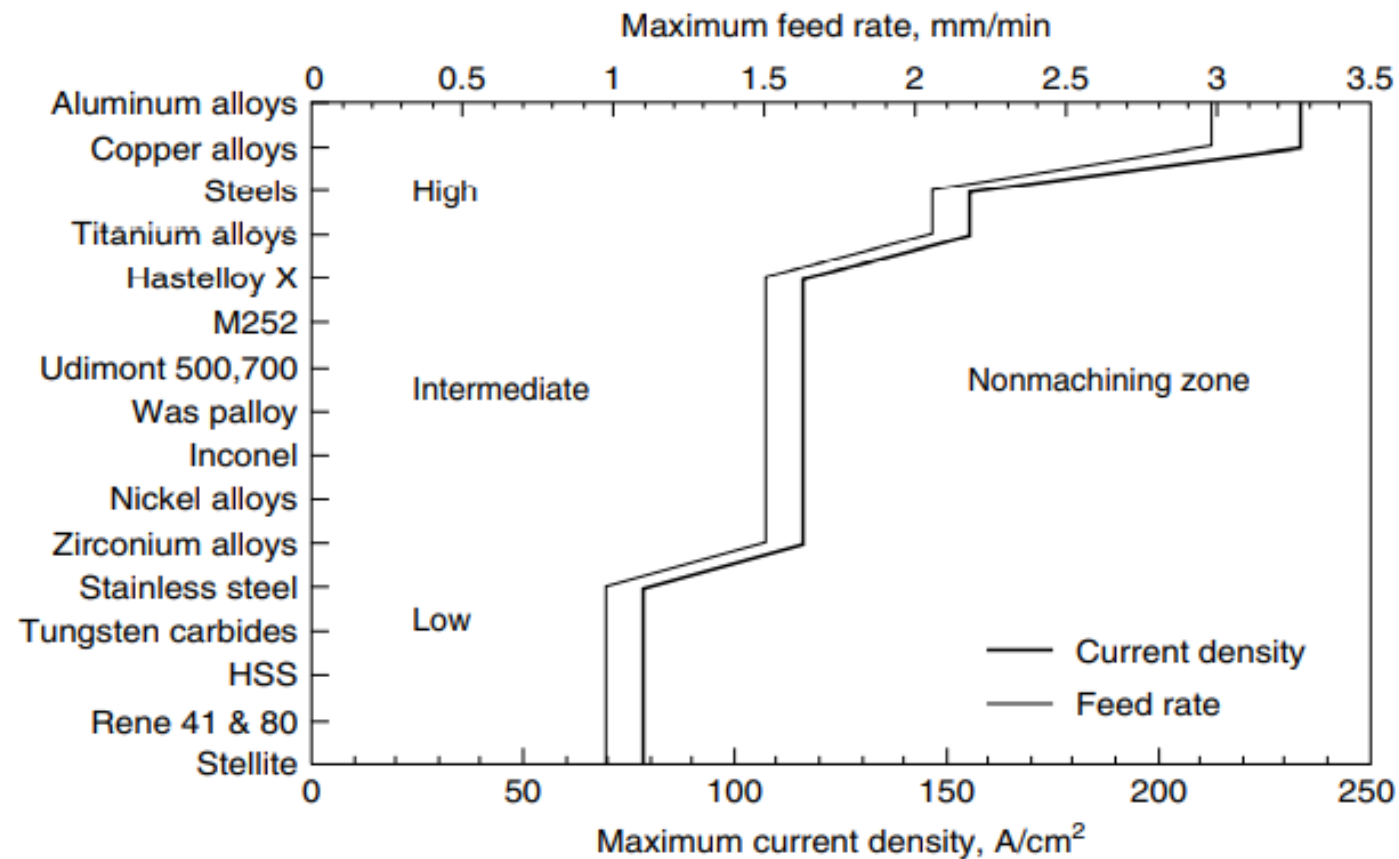
Material Removal Rate

- Material is mainly removed by Electrochemical dissoultion, while the machining action of the abrasive grits accounts for an additional 5 to 10 percent of the total material removal

- Material removal rate:

$$MRR = \frac{I}{F\rho}\frac{A}{v}$$

Material Removal Rate

Grinding Wheel

- Metal bonded grinding wheels have many advantages over resinoid bonded wheels

- In ECG wheel, the commonly used bonding materials are copper, brass, nickel, or copper impregnated resin. Such metal bonded wheels are effectively dressed using electrochemical process

- To prepare (or dress) them, reverse the current (or make the wheel as anode) and do the grinding on the scrap piece of metal. It will deplete the metal bond

- The commonly used abrasive is alumina (grit mesh size 60-80)

- ECG does not require frequent wheel dressing. Dissolution of bond metal usually makes mechanical shear unnecessary

Process Parameters

- Performance of ECG process depends on various process parameters
  - wheel speed,
  - workpiece feed,
  - electrolyte type,
  - concentration and delivery method,
  - current density,
  - wheel pressure, etc.

- With higher current density, both MRR and surface finish improve

- If the applied voltage is very high (usual range is 4-15 V), it may deteriorate surface' finish of the machined workpiece as well as damage the tool (grinding wheel)

Process Parameters

- If feed rate is higher than the required one, the abrasive particles will prematurely detach from the wheel, leading to excessive wheel wear

- If feed rate is lower than the required one, a large overcut (or poor tolerances) and poor surface finish will result

- The IEG is usually a quarter of a millimeter while using a freshly dressed wheel

- Surface speed of the wheel is in the range of 1200-1800 m/min

Advantage

- Increased MRR due to the added electrochemical effect
- Reduced tool wear and sharpening costs
- Less risk of thermal damage and distortion
- Absence of burrs
- Reduced wheel pressure which improves accuracy
- Good surface quality
- Production of narrow tolerances

Disadvantage

- Higher capital cost of the equipment

- Limited to electrically conductive materials

- Hazard due to corrosive nature of electrolyte, for that reason $NaNO_3$ of limited corrosion nature is used

- Necessity of electrolyte filtering and disposal

Electro Chemical Deburring

- Electrochemical deburring is generally employed for far away located as well as inaccessible places where other deburring processes are not effective

- This process involves the use of flowing electrolyte for conducting electric current for the electrochemical reaction to take place

- The electrolyte commonly used is either sodium chloride or sodium nitrate

- Because of the corrosive nature of the electrolyte and ferrous hydroxide released by the process, machines are built with noncorrosive materials

Working Principle

- When a voltage is applied between two metal electrodes immersed in an electrolyte, current flows through the electrolyte from one electrode to the other

- Unlike the conduction of electric current in the metals in which only the electrons move through the structure of the material, 'ions' (electrically charged groups of atoms) physically migrate through the electrolyte

- The transfer of electrons between the ions and electrodes completes the electrical circuit and also brings about the phenomenon of metal dissolution at the positive electrode or anode (workpiece)

Working Principle

- Metal detached atom by atom from the anode surface appears in the main body of the electrolyte as positive ions, or as precipitated semi-solid of the metal hydroxide, which is more common in electrochemical deburring process

- The tool is usually insulated on all surfaces except a part which is adjacent to the burrs

- The inter electrode gap (IEG) is usually kept in the range of 0.1-0.3 mm

- The deburring tool-tip should normally overlap with the area to be worked by 1.5 to 2.0 mm