ME338 – Manufacturing Process II
Lecture 10 : Electrochemical Machining (ECM) Processes

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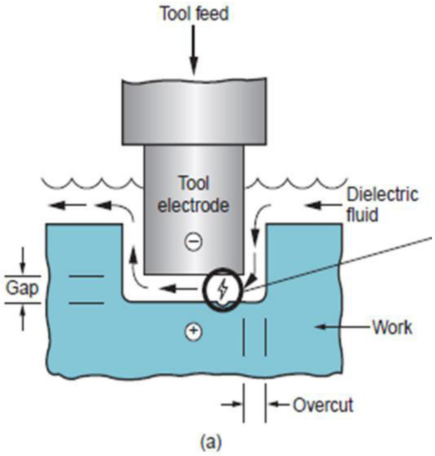
Recap: Electrodischarge machining

- Non-Traditional machining methods
  - Ductile materials : ECM, EDM
  - Brittle materials: USM, AJM
  - Textile, paper: WJC
- Electro-discharge machining
  - Melting and vaporization of a small amount of material by electrical spark
  - Material Removal rate MRR(mm^3/min) = $(4x10^4).I / T_m^{1.23}$
  - Wear rate of electrode W(mm^3/min) = $(11x10^3).I / T_e^{2.38}$
- DC 60-300 V, Inter-electrode gap 10-100 μm
- Electrical spark last about 1μs to 8 ms
- Resulted Temperature during electric spark: > 5000° C
- Pulse electrical supply
  - Resistance R, capacitance C – important parameter
  - Charging: $V_c = V_o\left(1 - e^{-\frac{t}{RC}}\right)$, $I_c = I_o e^{-t/RC}$
  - Discharging: $V_d = V_c e^{-t_d/Rm.C}$, $I_d = \frac{V_c}{R_m} e^{-t_d/Rm.C}$



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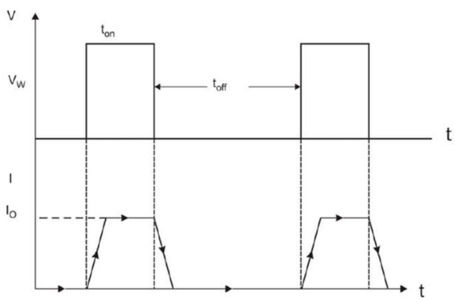
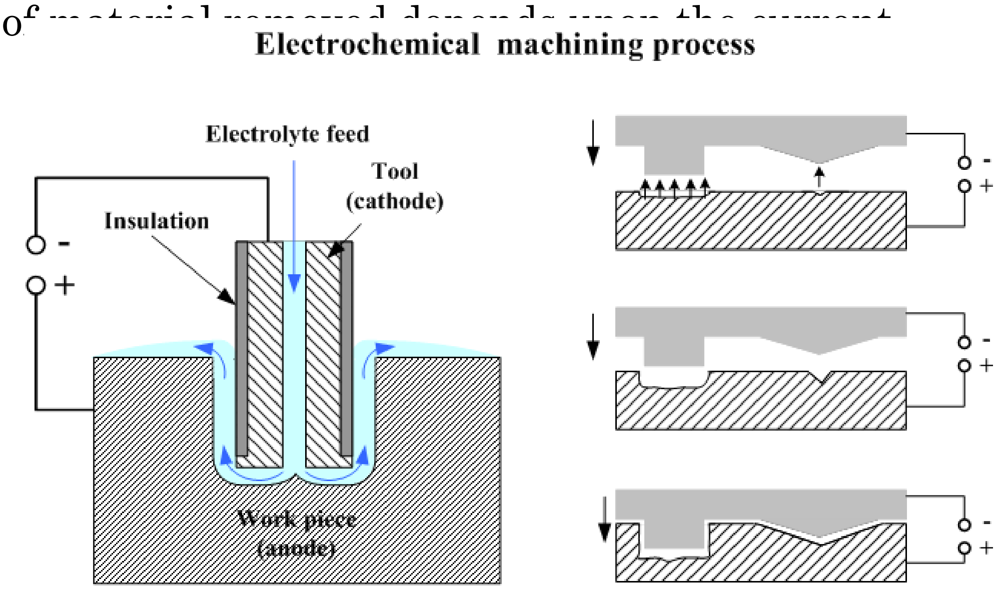


Electrochemical Machining (ECM)

- Popular “room temperature ” NTM for “hard-to-machine” conductive materials
  - Titanium aluminides, Inconel, high nickel and cobalt alloys
- Based on controlled atomic dissolution of a conductive material by electrochemical action of supplied electrical energy
- Amount of material removed depends upon the current



Applications of ECM

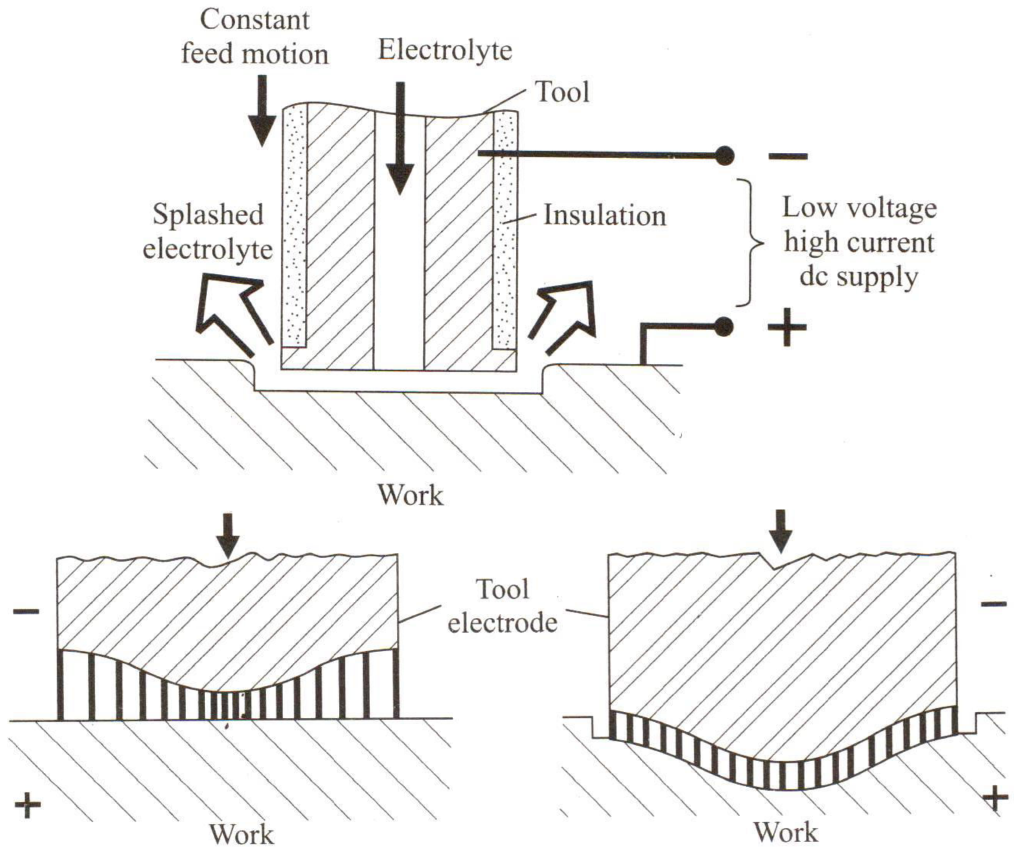

Features etched by ECM in Tungston


Turbine blades

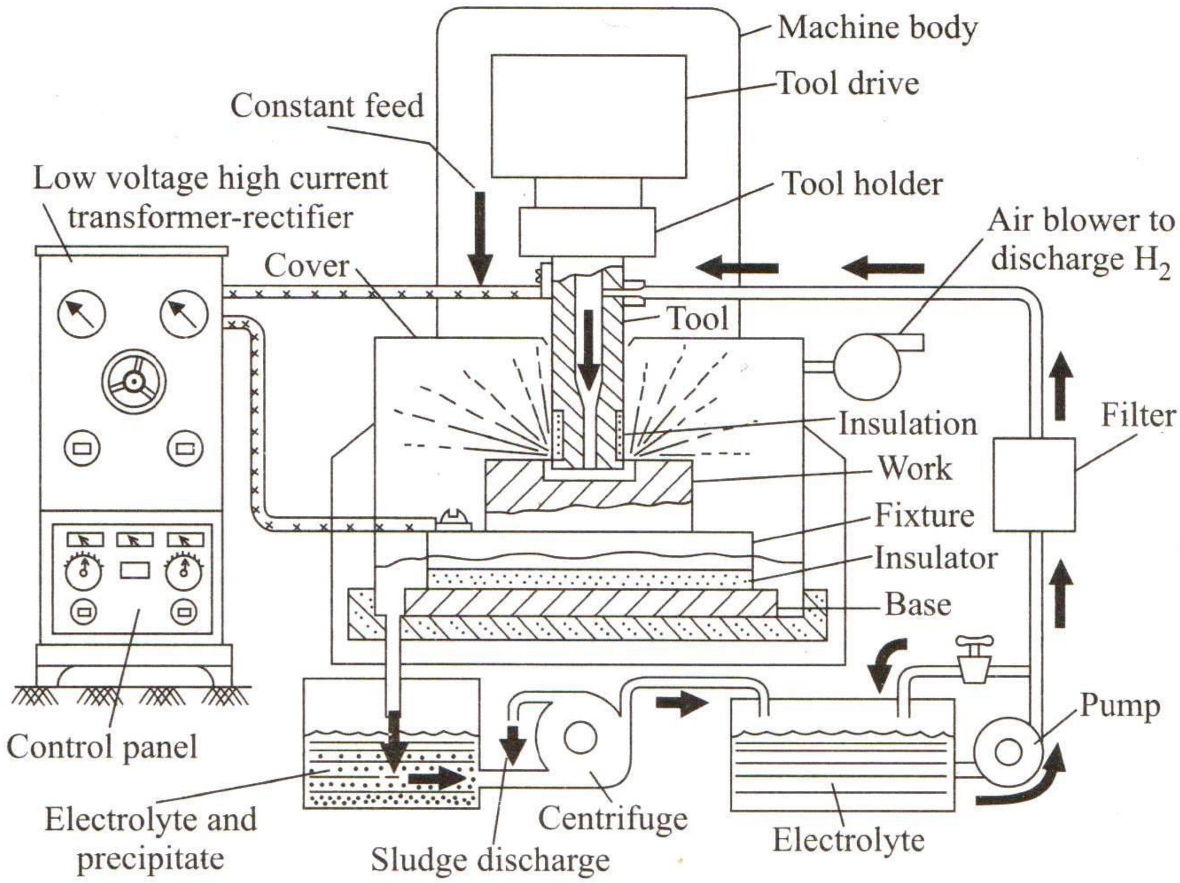

Bone screws – nickel based alloy


Gears made by ECM in Nickel based alloy

Electrochemical Machining



Electrochemical Machining - setup



Electrochemical Machining – Important features

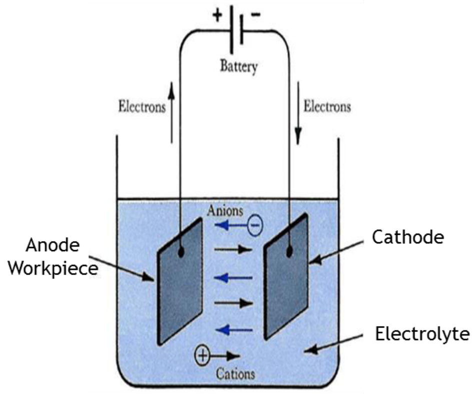
- Work material must be electrical conductive
- Electrolyte – conductive medium between cathode and anode
- when work-piece is connected anode, the electrochemical reactions will etch the material
- Used for hard-to-machine materials like inconel (Ni-Cr super alloy), tungsten, tungsten carbide. Smooth burr-free material removal
- Very popular in automotive and aerospace applications like machining of gas turbine blades, turbocharger rotor
- Also reverse-ECM or electrodeposition is frequently used for thin interconnects deposition in semiconductor/MEMS industry

Electrochemical Machining

- Three main parts of ECM:
  - Tool (cathode): brass, copper, bronze, stainless steel
  - Work piece (anode) ….
  - Electrolyte (medium)…
- A dc voltage (10-25 v) is applied across the gap between a pre-shaped cathode tool and an anode workpiece.
- The workpiece is dissolved by an electrochemical reaction to the shape of the tool.
- The electrolyte flows at high speed (10-60 m/s) through the gap (0.1-0.6 mm) to dissipate heat and wash away the dissolved metal ions.
- Metal ions are washed just before they have a chance to plate on the tool (cathode)

Faraday’s laws of electrolysis

- Material removal rate by Faraday’s laws of electrolysis
  - "The mass of a substance altered at an electrode during electrolysis is directly proportional to the quantity of electrical charge transferred at that electrode.”
  - For a given charge, material removed depends upon the chemical equivalent weight of that material



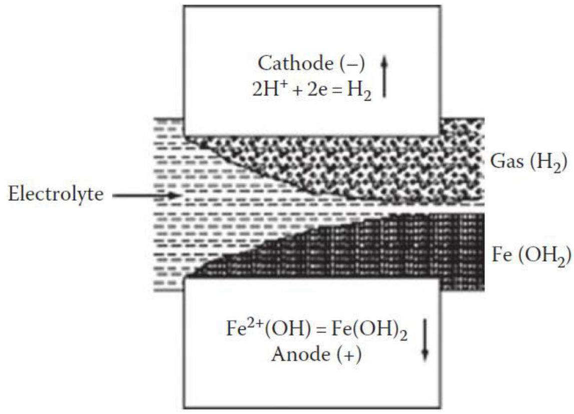
- Dissolution reaction of iron in a sodium chloride (NaCl) water solution:

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

At the anode: $Fe \rightarrow Fe^{++} + 2e$

At the cathode: $2H_2O + 2e \rightarrow H_2 + 2\,(OH)^-$

$$Fe + 2H_2O \rightarrow Fe\,(OH)_2 + H_2$$
$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$$



Faraday’s laws of electrolysis

- Material removal rate is determined by Faraday’s laws of electrolysis
  - Amount of material removed = m
  - Current passed through the electrolyte = I
  - Chemical gram equivalent weight = $Z = \frac{A}{n}$
  - A atomic weight, n number of valence electrons
  - Electrochemical machining time = t
  - Faraday constant = F (96500 Coloumbs)
- Amount of material removed on the anode $m = Z.I.t/F$
- Some part of the supplied current also used in other reactions (hydrogen gas formation); therefore actual material removal is less than the theoretical value.
  - This ratio is denoted by current efficiency (η), which is 90-99%
- Volumetric material removal rate (V’) will depend on the density (ρ) of the material
- $V' = \eta \frac{m}{t\rho} = \eta \frac{ZI}{F\rho}$

Theoretical Removal Rates in ECM

Metal	Atomic Weight	Valence	Density (g/cm^3)	Removal Rate (1000 A and 100% Current Efficiency[a]) Mass (kg/h)	Volume ($mm^3 \times 10^3$/min)
Aluminum	26.97	3	2.7	0.34	2.1
Beryllium	9.0	2	1.9	0.17	1.5
Copper	63.57	1	9.0	2.37	4.4
		2		1.18	2.1
Chromium	51.99	2	7.19	0.97	2.3
		3		0.65	1.5
		6		0.32	0.78
Cobalt	58.93	2	8.85	1.1	2.1
		3		0.74	1.38
Iron	55.85	2	7.9	1.04	2.3
		3		0.69	1.5
Magnesium	24.31	2	1.7	0.45	4.4
Molybdenum	95.94	3	10.2	1.19	2.0
		4		0.89	1.5
		6	10.2	0.60	1.0
Nickel	58.71	2	8.9	1.09	2.1
		3		0.73	1.3
Niobium	92.91	3	8.6	1.16	2.3
		4		0.87	1.6
		5		0.69	1.3
Silicon	28.09	4	2.33	0.26	1.86
Tantalum		5	16.6	1.35	1.3
Tin	118.69	2	7.30	2.2	2.88
		4		1.1	2.52
Titanium	47.9	3	4.5	0.59	2.1
		4		0.45	1.6
Tungsten	183.85	6	19.3	1.14	1.0
		8		0.86	0.8
Zinc	65.37	2	7.13	1.22	2.88

Gram equivalent weight of alloys

- For pure metal, material removed m can be find by Faraday's law
- How about alloys ?
  - Lets say, there are several metals having $X_1\%, X_2\%......X_i\%$.
  - Their atomic weights $A_1, A_2....A_i$
  - No of electrons coming out $n_1, n_2, ...n_i$
  - Their respective chemical equivalent weight $Z_1, Z_2....Z_i$
  - Volumetric material removal rate per unit charge

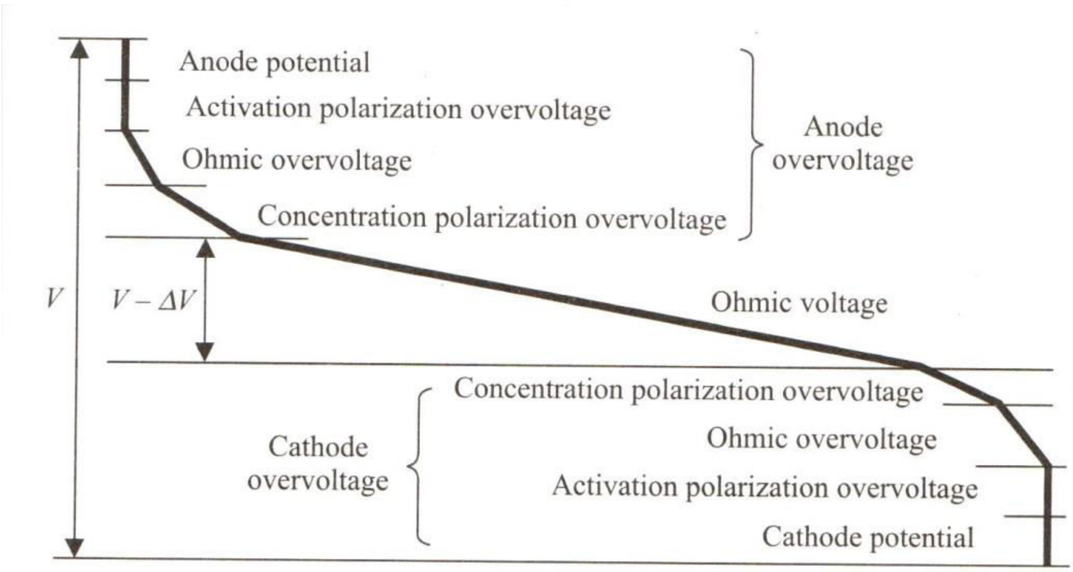
$$V' = \frac{100}{\rho F}\left(\frac{1}{\sum x_i n_i / A_i}\right) cm^3$$

ρ - Equivalent density of alloy

Gram equivalent weight of alloys

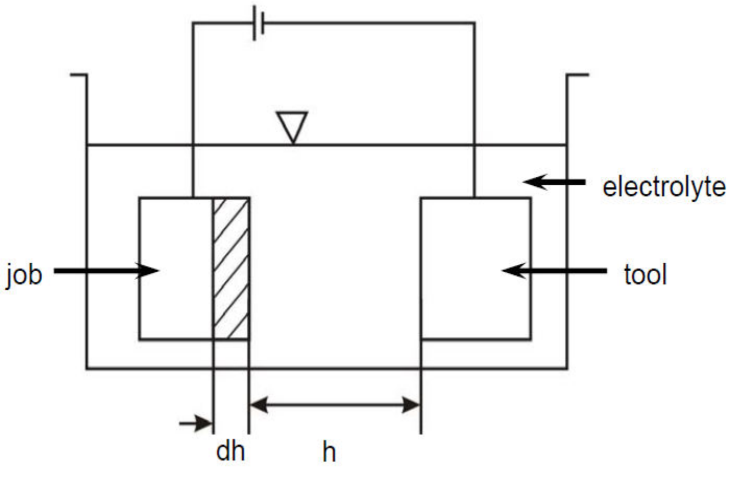
- Percentage of weight method:
  - The sum of the chemical equivalents of each element (Z_i)in the alloy, multiplied by its respective proportion by weight (X_i), gives a value for the chemical equivalent weight of the alloy (Z_{alloy})
  - $Z_{alloy} = \frac{1}{100}\sum Z_i$; $Z_{alloy} = \frac{1}{100}\sum\left[X_1\frac{A_1}{n_1} + X_2\frac{A_2}{n_2} + \cdots\right]$
- The total material removed (m) in time t, $m = \frac{Z_{alloy}It}{F}$
- Superposition of charge method:
  - The electrical charge required by each element (qi) to dissolve their individual mass is equal to the total charge (q) required to dissolve 1g of the alloy
  - If X_1, X_2, .. are the percentage composition of the material present in alloy then
  - Charge q_1 required to remove material (X_1): $q_1 = F\frac{X_1}{Z_1}$
  - Charge q for removing 1g of alloy: $q = F\frac{100}{Z_{alloy}}$
  - $Z_{alloy} = \frac{100}{\sum X_1({}^{n_1}/_{A_1}) + X_2({}^{n_2}/_{A_2}) + \cdots\ldots\ldots}$

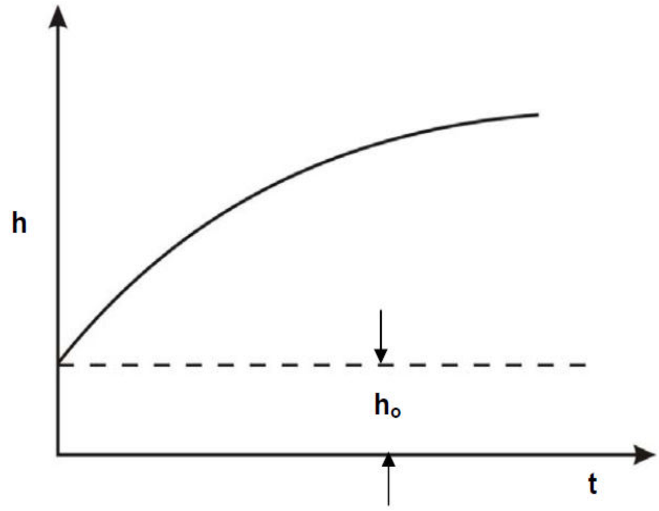
Voltage drop between electrodes



- Some part of the applied electrical potential is used to overcome the overpotential near the electrode surface (typically <10%)
- Electrode potential (V),
- Over-potential (ΔV)
  - Activation polarization, concentration polarization, Ohmic overvoltage
- Net ohmic voltage (V- ΔV) is used in material removal

Dynamics of ECM – with no tool feeding





- $m = Z.I.t/F$ .... (1)
- If A is cross-sectional area, p is density of work-piece, dh is material removed in dt time
- $A.p.dh = Z.I.dt/F$ .... (2)
- Amount of current passed through the electrode will depend upon the applied voltage (V), and inter-electrode gap (h). If specific resistivity of electrolyte is Ω,

  then $I = V/R = V.A/h.\Omega$ .... (3)

Dynamics of ECM – with no tool feeding

In electrolysis:

$A.p.dh = Z.V.A.dt/F.h.\Omega$

$h.dh = (Z.V/p.F.\Omega).dt$

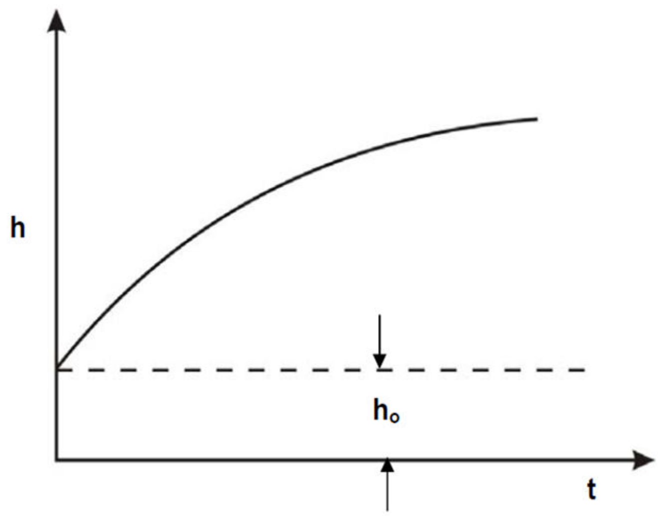
$Z.V/p.F.\Omega$ is a constant = c

$h.dh = c.dt$ OR $dh/dt = c/h$

at $t = 0, h = h_i$, at $t = t, h = h_f$

$h_f{}^2 - hi^2 = 2ct$

<u>The interelectrode gap increases with time t</u>



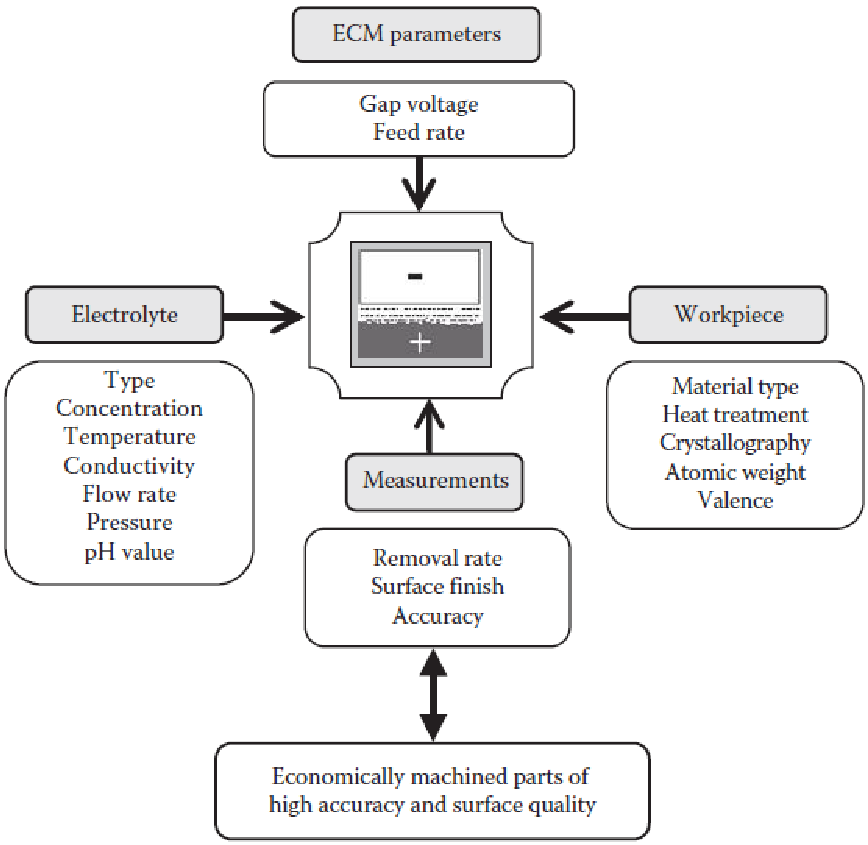
With constant feed:

- If feed f is provided then,
- Change in gap with time:
  - $dh/dt = c/h - f$

Heat removal during ECM Process

- As the high current (I) passes through a resistive electrolyte (say resistance R) in the interelectrode, temperature of the electrolyte increases due to the Joules heating (I^2R)
  - Electrolyte starts boiling, which will affect the process
  - Resistance R will depend upon the conductivity of the electrolyte and the gap
- Cooling in the machining zone is provided by the electrolyte
  - Higher electrolyte flow rate (V'), higher cooling action
- Permissible temperature rise in the electrolyte should be below the boiling point of the electrolyte
- Heat input due to joules heating (I^2R)= heat required to increase the temperature $[\rho V' C_{ele}(T_{boil} - Troom)]$

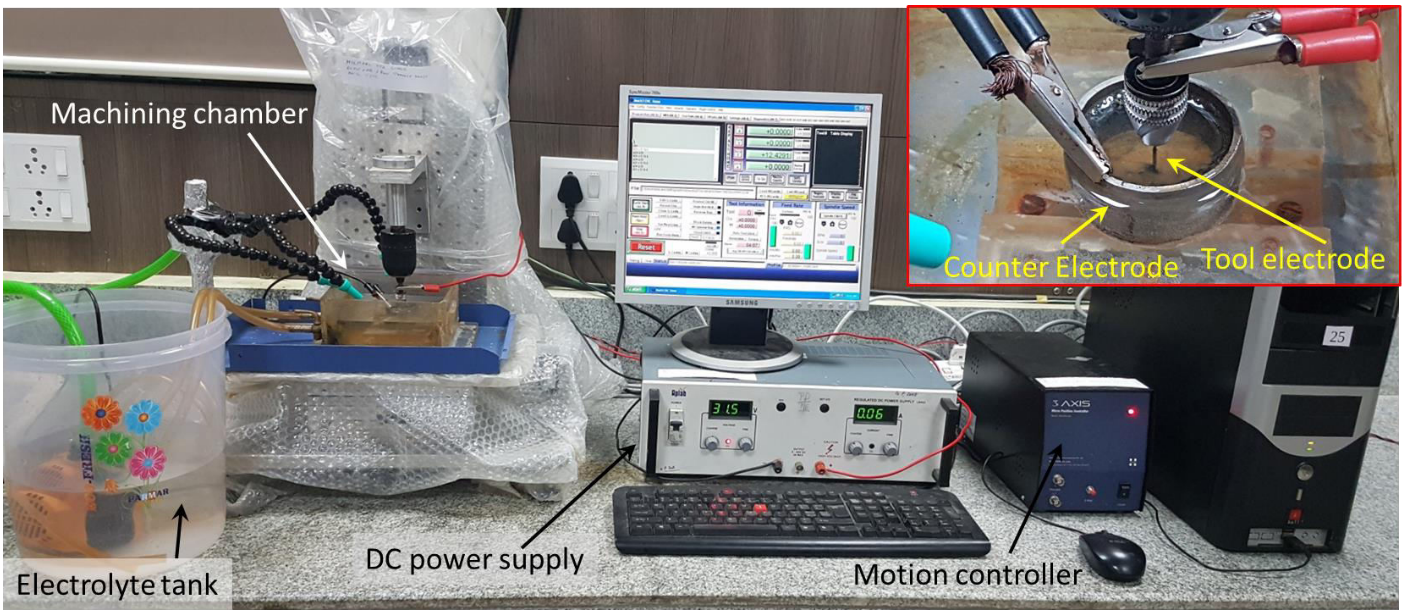
Parameters affecting MRR



Pros and Cons of ECM

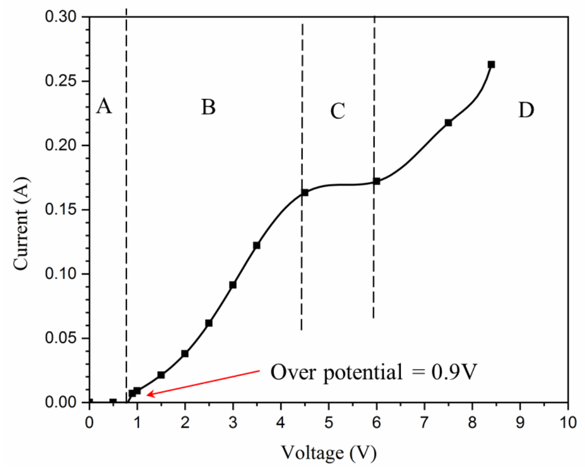
- Pros:
  - Excellent surface finish as material is removed atom by atom
  - Little surface damage to the workpiece,
  - No burrs as in conventional machining,
  - Low tool wear (the only tool wear results from the flowing electrolyte),
  - Relatively high metal removal rates for hard and difficult-to-machine metals like Inconel, high-nickel alloys, titanium
- Cons:
  - Workpiece must be conductive
  - Significant cost of electrical power to drive the operation,
  - Problems of disposing of the electrolyte sludge

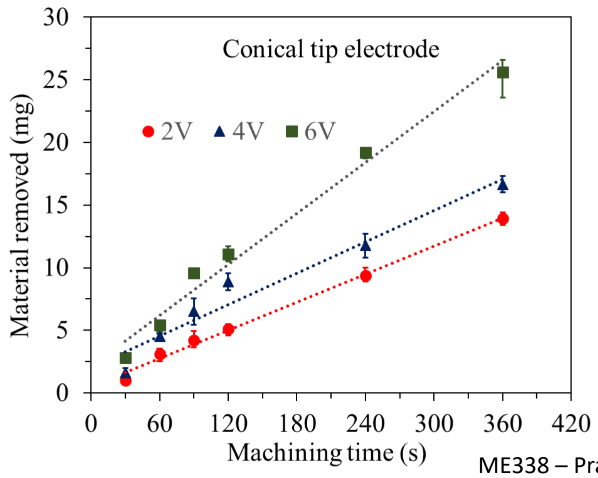
ECM related research @ IIT B

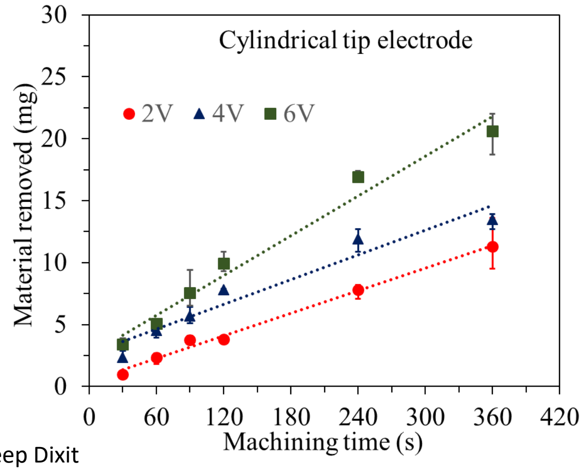


Microtool fabrication by controlled ECM

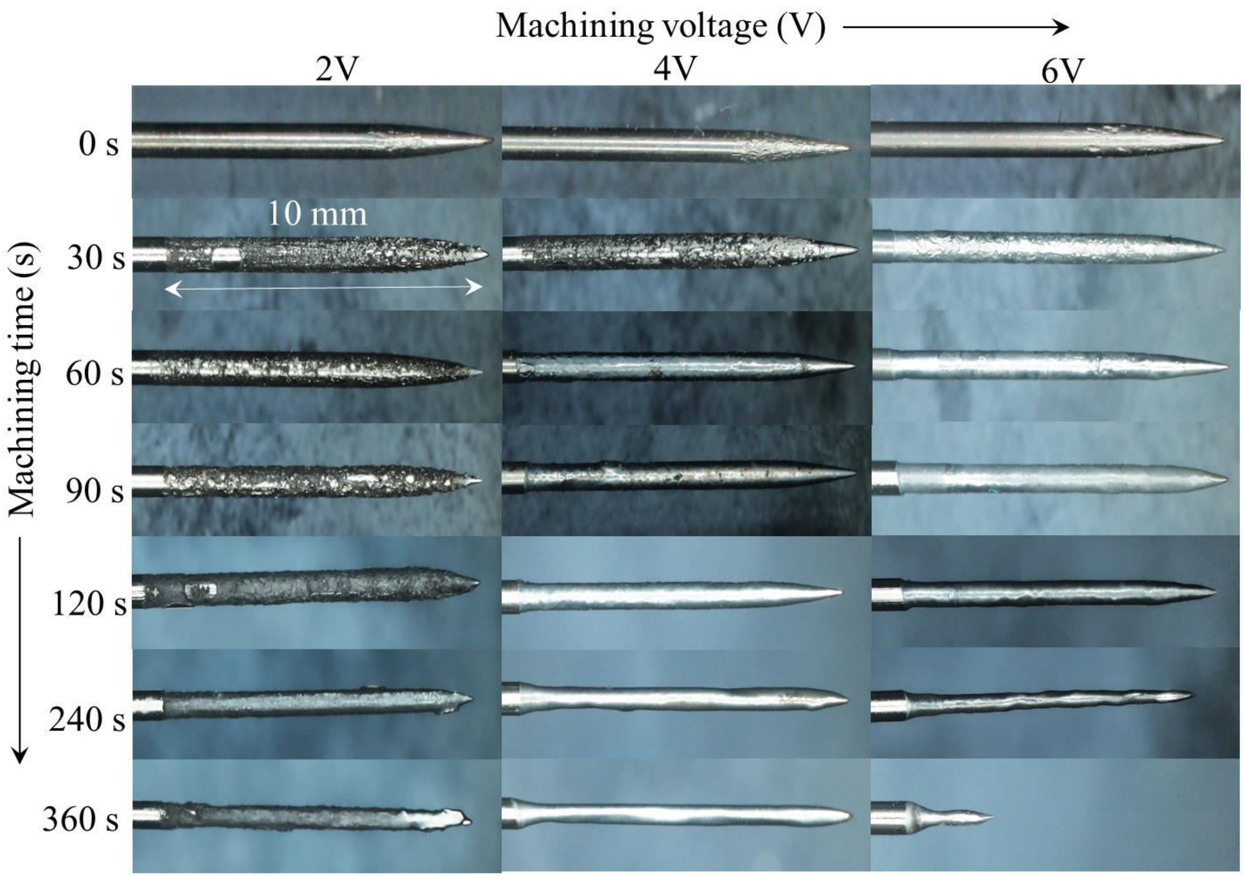
- Workpiece: conical & Cylindrical needle
- Electrolyte: 5% NaCl (%weight)
- Continuous DC
- Immersion depth: 10 mm



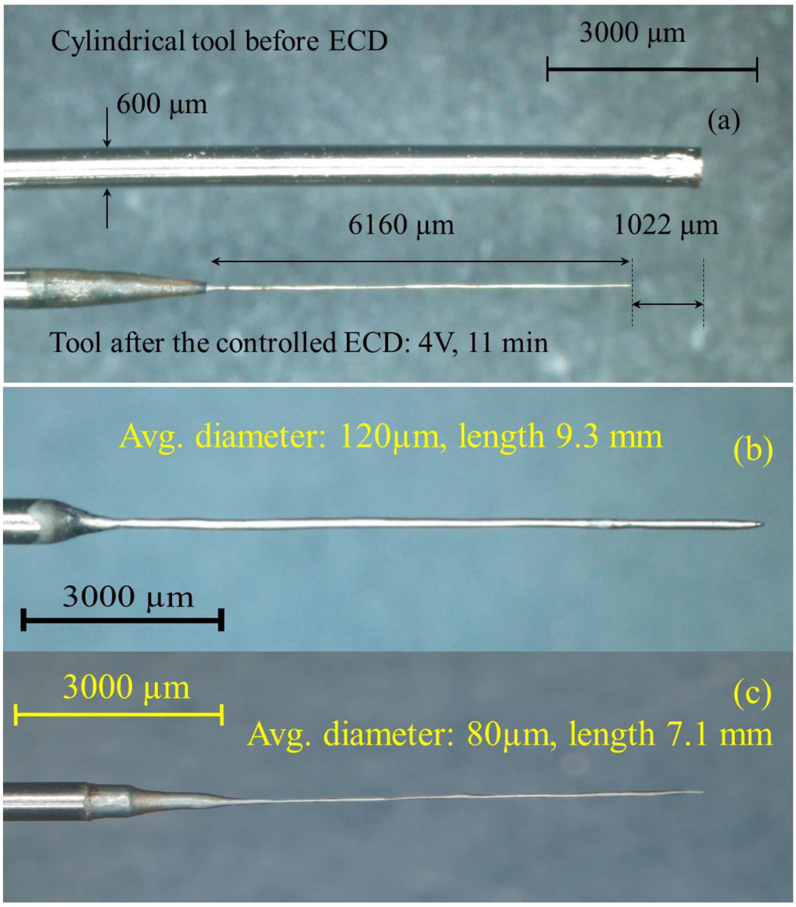


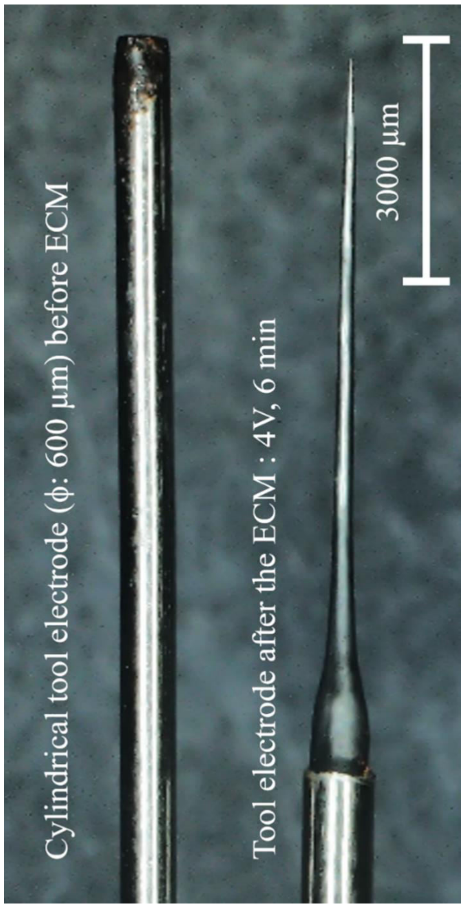


Tool electrodes at varying ECM parameters



Fabricated tool electrodes





Use of fabricated tool electrodes in ECDM