Non-Traditional Chemical and Thermal Machining

Introduction

- Machining is a broad term to describe removal of material from a workpiece.
- Machining categories:
  - Cutting involves single-point or multipoint cutting tools, each with a clearly defined geometry.
  - Abrasive processes, such as grinding.
  - Nontraditional machining, utilizing electrical, chemical, and optical sources of energy.

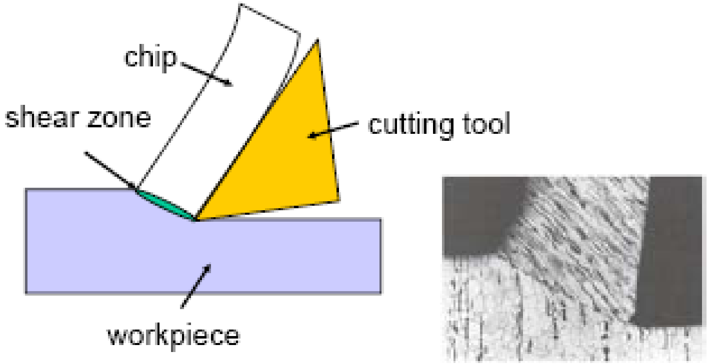
Nontraditional Machining

- Chemical Machining
- Electrochemical Machining (ECM)
- Electrical-Discharge Machining (EDM)
- High-Energy-Beam Machining
  - Laser-beam machining (LBM)
  - Electron-beam machining (EBM)

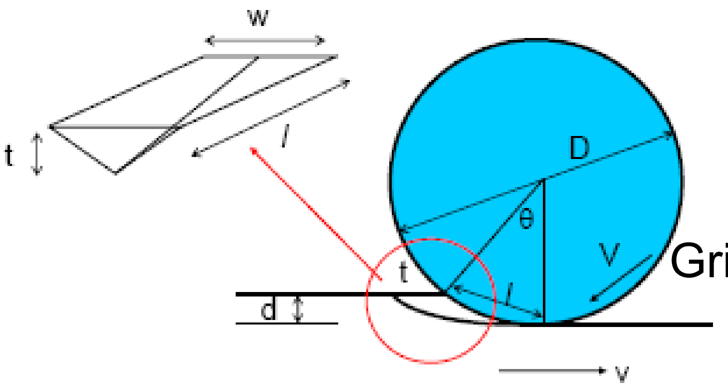
Traditional vs. Nontraditional

- Primary source of energy
  - Traditional: mechanical.
  - Nontraditional: electrical, chemical, optical
- Primary method of material removal
  - Traditional: shearing
  - Nontraditional: does not use shearing (e.g., abrasive water jet cutting uses erosion)

Water jet machining



2D cutting process



Grinding

Why Nontraditional Machining?

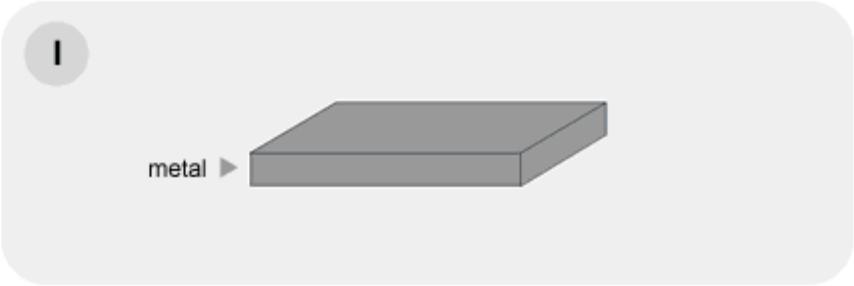
- Situations where traditional machining processes are unsatisfactory or uneconomical:
  - Workpiece material is too hard, strong, or tough.
  - Workpiece is too flexible to resist cutting forces or too difficult to clamp.
  - Part shape is very complex with internal or external profiles or small holes.
  - Requirements for surface finish and tolerances are very high.
  - Temperature rise or residual stresses are undesirable or unacceptable.

Chemical Machining (CM)

- Chemical machining, basically an etching process, is the oldest nontraditional machining process.
- Material is removed from a surface by chemical dissolution using chemical reagents, or etchants, such as acids and alkaline solutions.
- The workpiece is immersed in a bath containing an etchant. The area that are not required to be etched are masked with “cut and peel” tapes, paints, or polymeric materials.
- In chemical milling, shallow cavities are produced on plates, sheets, forgings, and extrusions for overall reduction of weight (e.g., in aerospace industry). Depths of removal can be as much as 12 mm.

CM (Cont.)

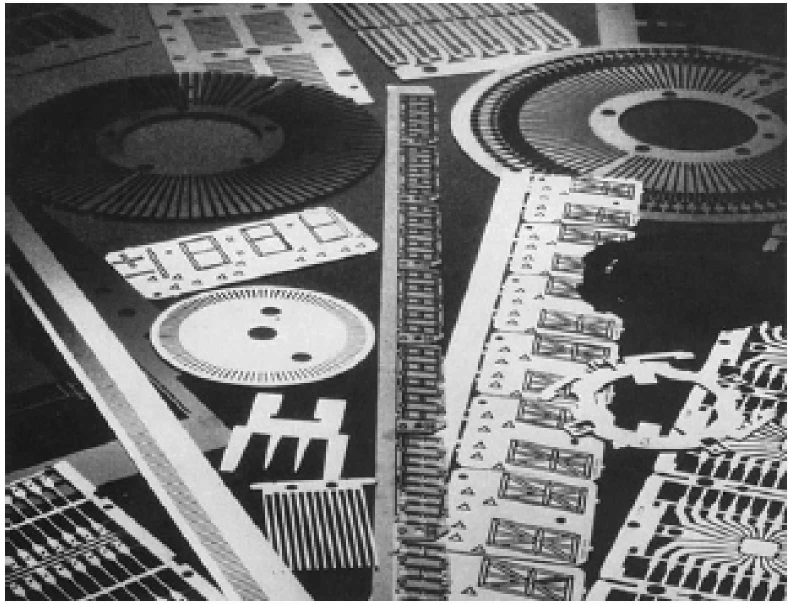
- Chemical blanking is used to produce features which penetrate through the material via chemical dissolution. The metal that is to be blanked is
  - thoroughly cleaned with solvents.
  - coated and the image of the part is imprinted.
  - soaked in a solvent that removes the coating, except in the protected areas.
  - spray etched to dissolve the unprotected areas and leave the finished part.



Chemically cleaned surface

CM (Cont.)

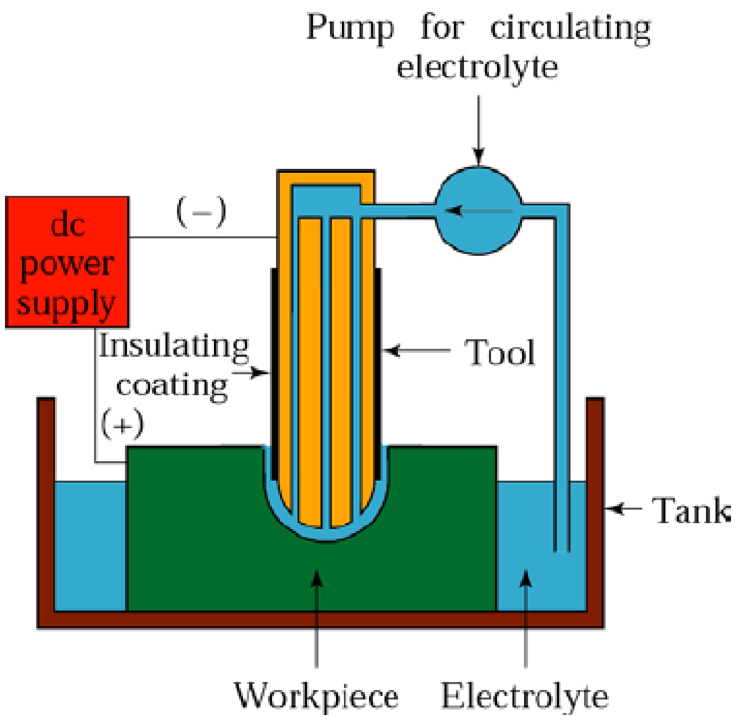
- Typical applications
  - Chemical blanking: burr-free etching of printed-circuit boards (PCB), decorative panels, thin sheet-metal stampings, and the production of complex or small shapes.
  - Chemical milling: weight reduction of space launch vehicles.



Pros: low setup, maintenance, and tooling costs; small, delicate parts can be machined; suitable for low production runs on intricate designs.

Cons: slow (0.025-0.1 mm/min); surface defects; chemicals can be extremely dangerous to health.

Electrochemical Machining (ECM)



- Process description:
  - In ECM, 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.

ECM (Cont.)

- Pros: high shape complexity possible, high MRR possible, high-strength materials, mirror surface finish possible.
- Cons: workpiece must be electrically conductive; very high tooling (dedicated) and equipment costs; high power consumption.
- Applications: complex cavities in high-strength materials, esp. in aerospace industry for mass production of turbine blades.

ECM (Cont.)

- The material removal rate by ECM is given by:

$$MRR = C\, I\, \eta$$

where, MRR=mm^3/min, I=current in amperes,

η=current efficiency, which typically ranges from 90-100%,

C is a material constant in mm^3/A·min.

Feed rate (mm/min): $f = MRR / A_0$

Assuming a cavity with uniform cross-sectional area A_0

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

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

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.

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

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

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

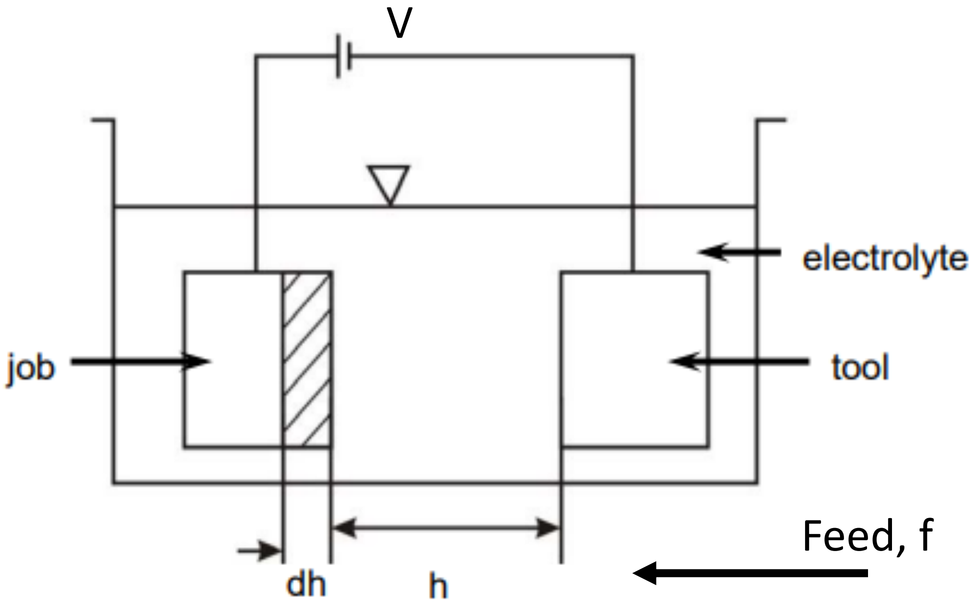
Now over a small time period 'dt' a current of I is passed through the electrolyte and that leads to an electrochemical dissolution of the material of amount 'dh' over an area of S

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

k= electrical conductivity (inverse proportional of resistivity)

S= area of electrode

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



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,

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

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

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

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

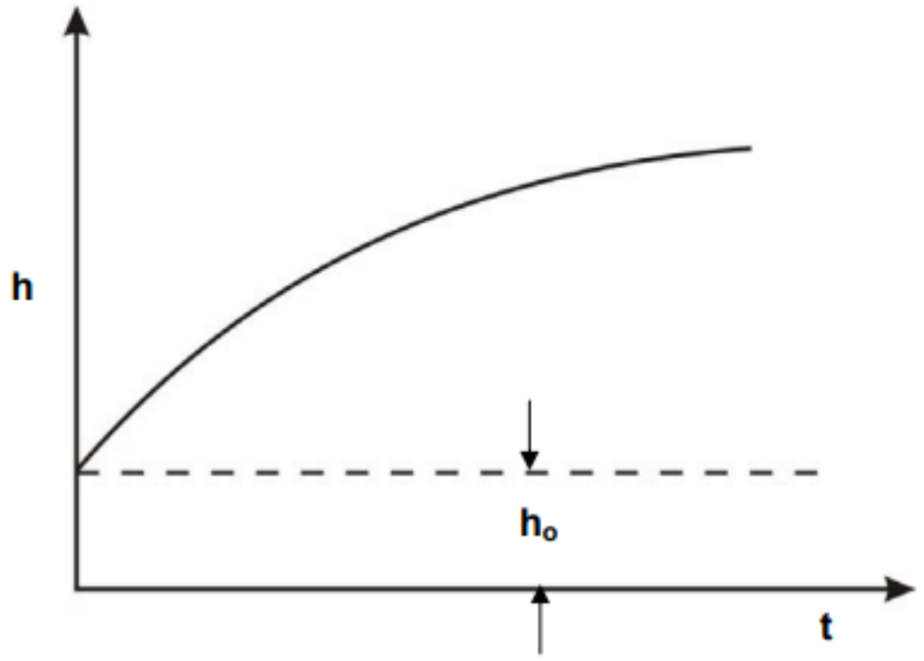
Dynamics of Electrochemical Machining

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



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,

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

Initial condition $t' = 0 \quad h' = h_0' \quad \mathrm{K} = h_0' + \ln(h_0' - 1)$

$$t' = h_0' - h' + \ln\frac{(h_0' - 1)}{(h' - 1)}$$

Dynamics of Electrochemical Machining

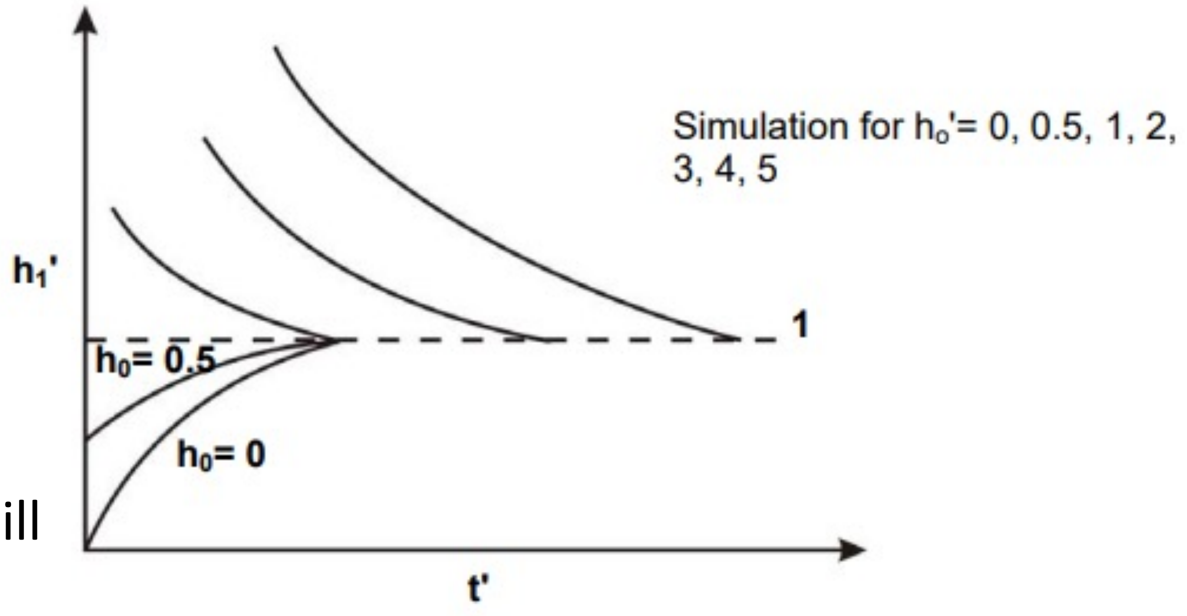
Self-regulating feature of the ECM process,

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

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

- 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



Variation in steady state gap with time for different initial gap

Dynamics of Electrochemical Machining

If f = MRR1,

- stable machining will take place and IEG will be equal to the equilibrium gap

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_e (electrolyte temperature) can be evaluated as:

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

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

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

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 :

$$P = q\rho_e C_e (T_e - T_i)$$

where, q is the volumetric flow rate of electrolyte

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

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

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

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:

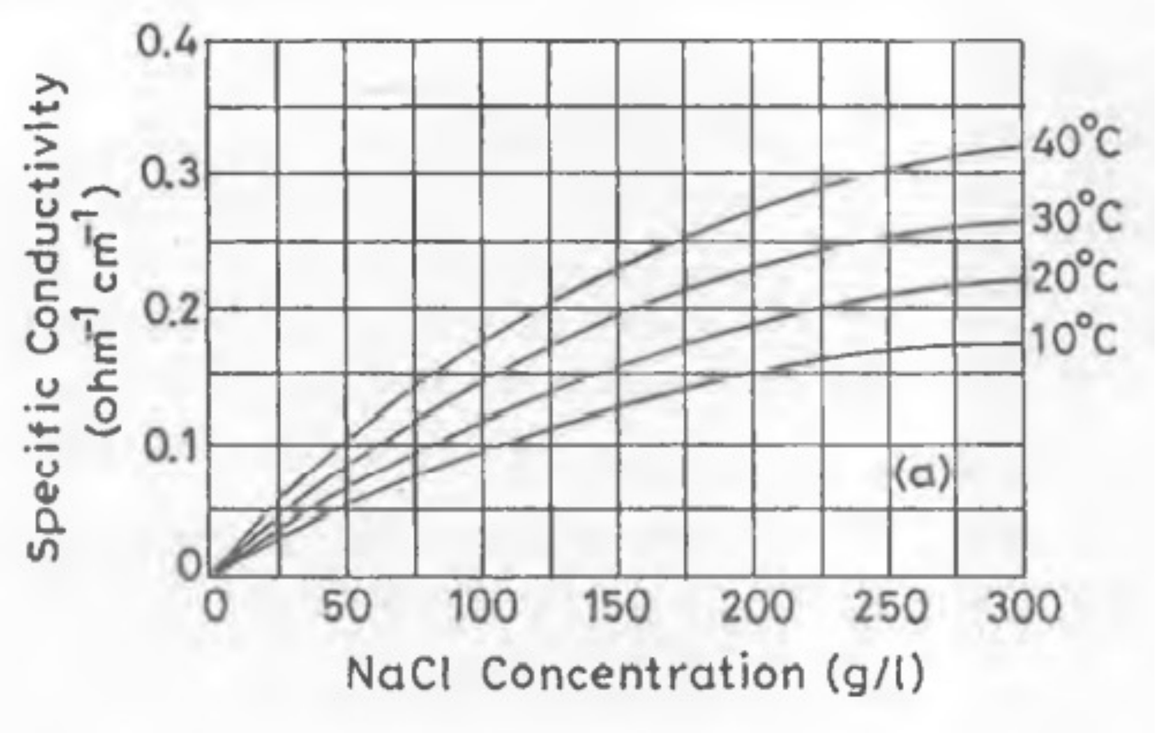
$$f_m = \frac{I_m}{F\rho S}\frac{A}{v}$$

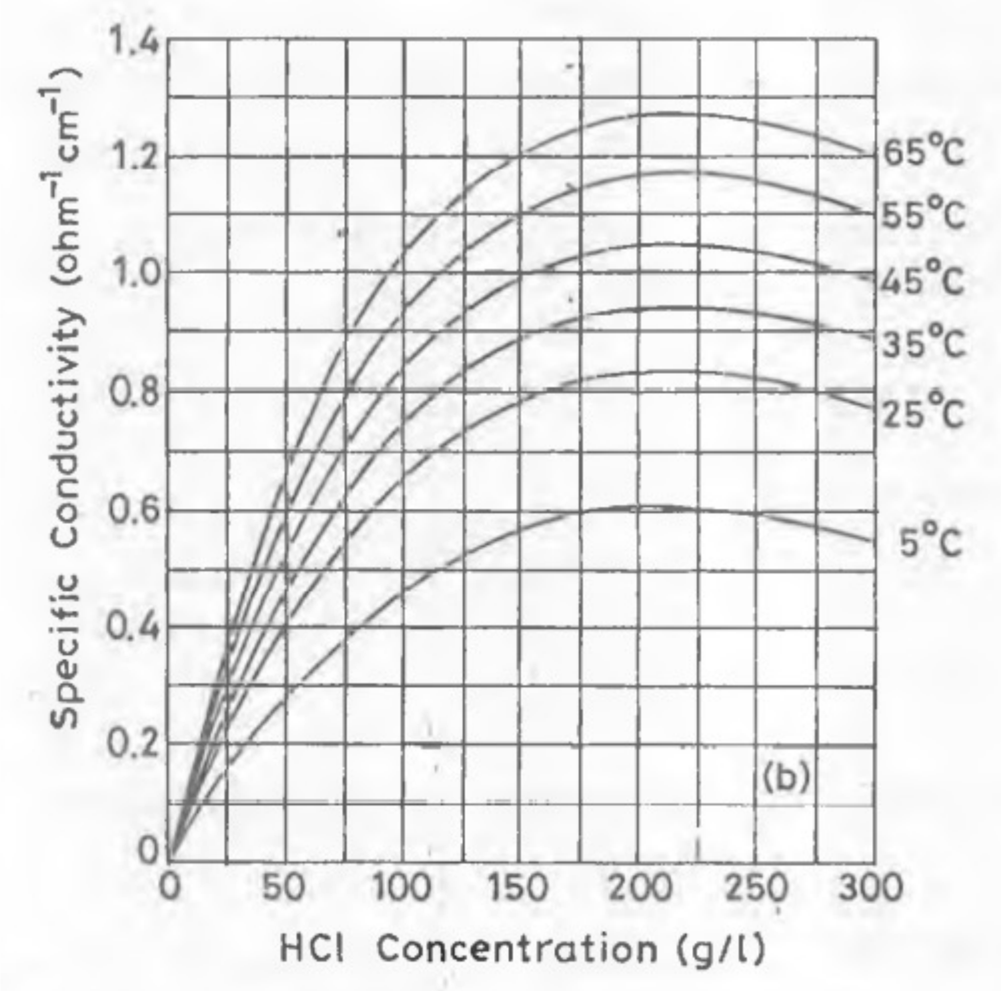
$$f_m = \frac{1}{F\rho}\frac{A}{v}\sqrt{\frac{q\rho_e C_e (T_b - T_i)k}{hS}}$$

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

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

Effect of Temperature on Electrolyte Conductivity (k)



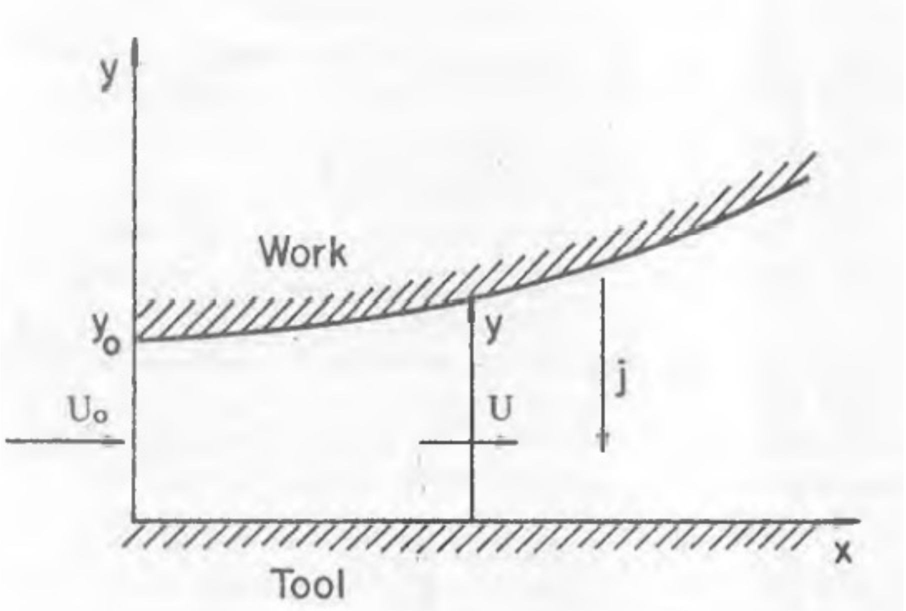


Effect of Electrolyte Conductivity (k)

- Using the law of conservation of heat, temperature gradient along the path of electrolyte flow can be derived as follows:

$$I^2R = U\rho_e C_e(\Delta T)wh$$

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

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

Effect of Electrolyte Conductivity (k)

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

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

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

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

Conductivity of the electrolyte varies linearly with temperature

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

Effect of Electrolyte Conductivity (k)

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

$$\frac{\mathrm{dT}}{(1 + \alpha(\mathrm{T} - \mathrm{T}_0))} = L\,k_0 dx$$

Integrating both side,

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

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

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:

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

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

EDM-History

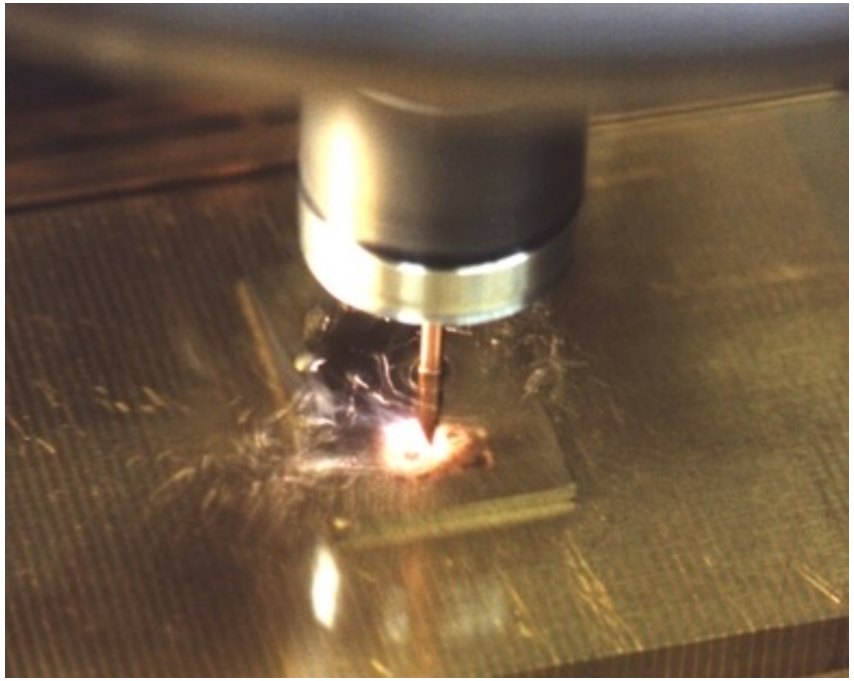
The origin of electrical discharge machining goes back to 1770, when English scientist Joseph Priestly discovered the erosive effect of electrical discharges. In 1943, Soviet scientists B. Lazarenko and N. Lazarenko had the idea of exploiting the destructive effect of an electrical discharge and developing a controlled process for machining materials that are conductors of electricity. With that idea, the EDM process was born.

Mr. & Mrs. Lazarenko at the presentation of the Eleroda D1at
the EMO exhibition in Milan Italy.

First industrial EDM machine in the world.

Mrs. Lazarenko

Electrical Discharge Machining (EDM)

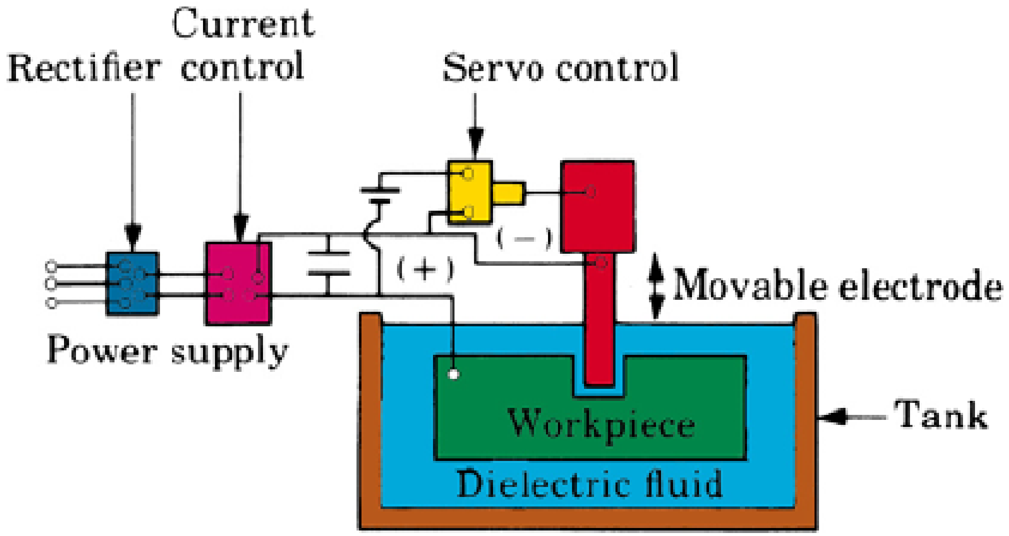


EDM is a thermal erosion process whereby material is melted and vaporized from an electrically conducive workpiece immersed in a liquid dielectric with a series of spark discharges between the tool electrode and the workpiece created by a power supply.

EDM is one of the most accurate while quite affordable mfg process.

EDM (Cont.)

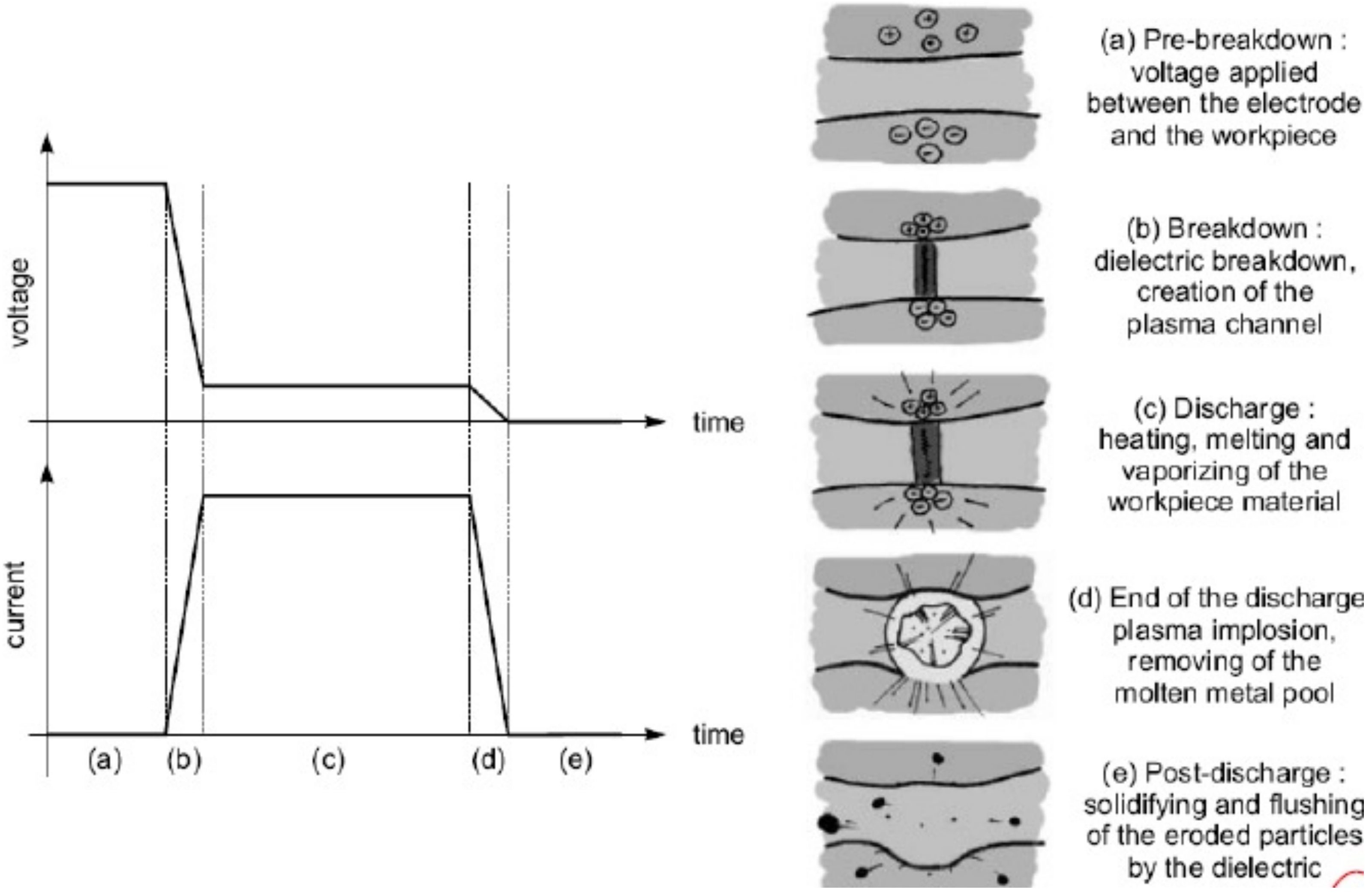
The EDM system consists of a shaped tool or wire electrode, and the part. The part is connected to a power supply to create a potential difference between the workpiece and the tool.



When the potential difference is sufficiently high, a transient spark discharges through the fluid, removing a very small amount of metal from the workpiece.

The dielectric fluid 1) acts as an insulator until the potential is sufficiently high, 2) acts as a flushing medium, and 3) provides a cooling medium.

Process-Basics



EDM (Cont.)

MRR is basically a function of the current and the melting point of the workpiece material. The three properties that affect are:

K (thermal conductivity), ρ (electrical resistivity) and Tm (melting temp)

An approximate empirical relationship is:

$$MRR = 4\times10^4\, I\, T_w^{-1.23}$$

MRR=mm^3/min

I=current in amperes

T_w=melting point of workpiece (ºC)

<u>Wear rate</u> of electrode:

$$W_t = 11\times10^3\, I\, T_t^{-2.38}$$

W_t=mm^3/min

T_t=melting point of electrode material (ºC)

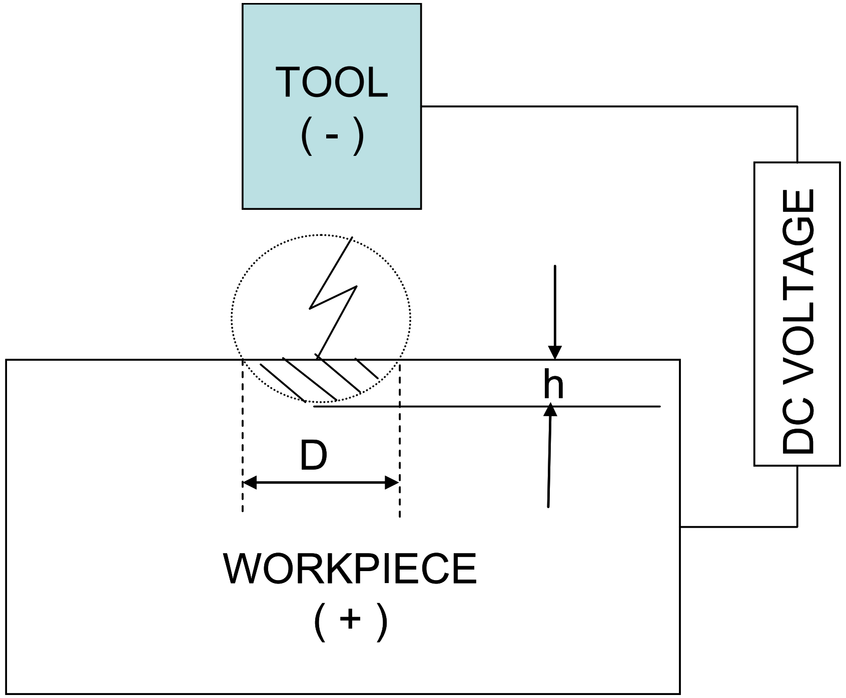
<u>Wear ratio</u> of workpiece to electrode:

$$R = 2.25\, T_r^{-2.3}$$

T_r=ratio of workpiece to electrode melting points (ºC)

MRR - EDM

- Experimental Approach



Scheme of Crater Formation

Metal removal is function of pulse energy and frequency:

$h = K_1 W^n$

$D = K_2 W^n$

where W = Pulse energy, J
h = height of crater, mm
D = diameter of crater, mm
K_1, K_2 = constants depending on electrode materials and dielectric
n = constant depending on work tool combination

The crater volume from geometry,

$$V_c = \frac{\pi}{6} h \left(\frac{3}{4} D^2 + h^2 \right)$$

$$V_c = \frac{\pi}{6} K_1 \left(\frac{3}{4} K_2^{\ 2} + K_1^{\ 2} \right) W^{3n}$$

$$MRR = \eta f \frac{\pi}{6} K_1 \left(\frac{3}{4} K_2^{\ 2} + K_1^{\ 2} \right) W^{3n}$$

***MRR* = $V_c f \eta$**

where f = frequency of operation and η = efficiency

Volume of the crater

In[15]:= $\int_{-r}^{-(r-h)} \pi \left(r^2 - y^2\right) dy$

Out[15]= $-\frac{h^3 \pi}{3} + h^2 \pi r$

In[17]:= $\int_{0}^{h} \pi \left(2\, r\, h - h^2\right) dh$

Out[17]= $-\frac{h^3 \pi}{3} + h^2 \pi r$

$$-\frac{h^3 \pi}{3} + \frac{h}{2} \pi \left(\frac{D^2}{4} + h^2\right)$$

In[19]:= $\text{FullSimplify}\left[-\frac{h^3 \pi}{3} + \frac{h}{2} \pi \left(\frac{D^2}{4} + h^2\right)\right]$

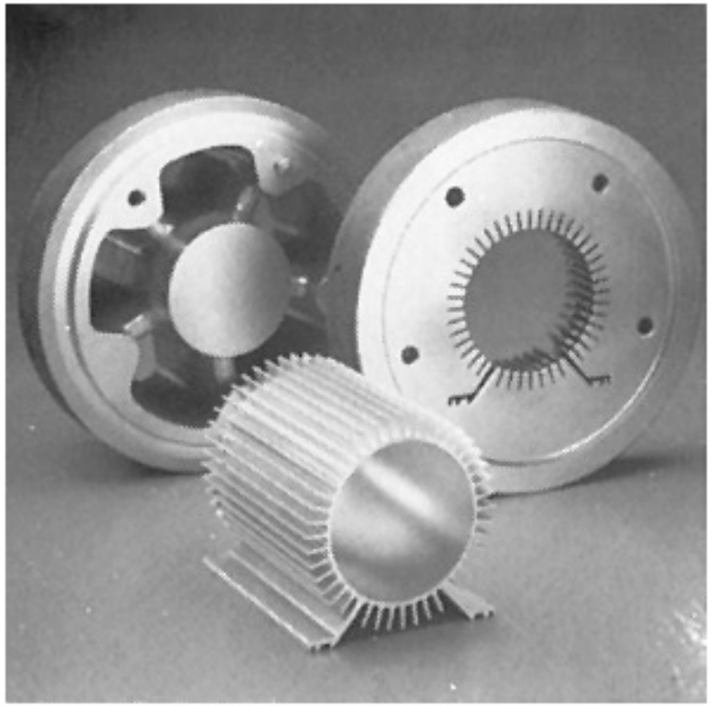
Out[19]= $\frac{1}{24} h \left(3 D^2 + 4 h^2\right) \pi$

EDM Process Capability

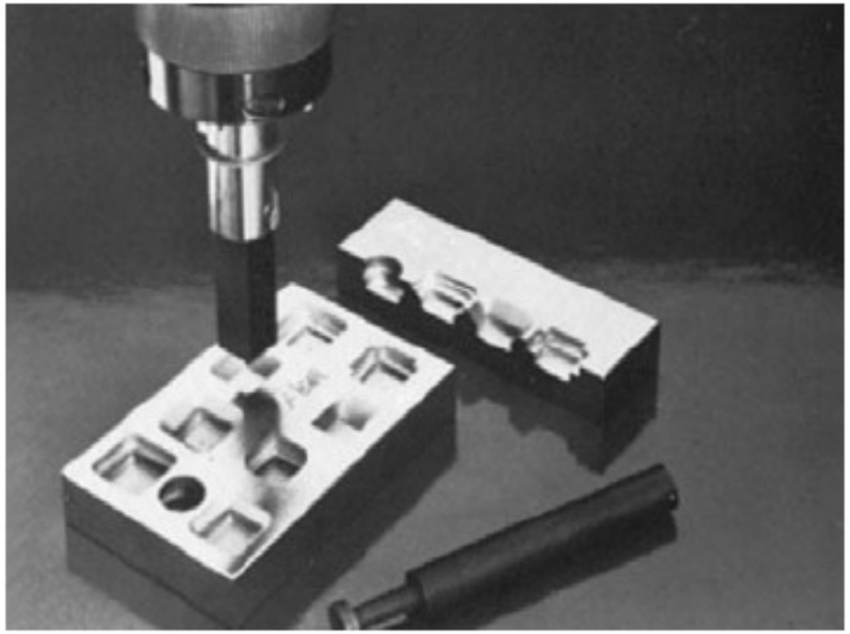
- MRR
  - Range from 2 to 400 mm^3/min. High rates produce rough finish, having a molten and recast structure with poor surface integrity and low fatigue properties.
- Dimensional Tolerances
  - Function of the material being processed
  - Typically between ± 0.005 - ± 0.125 mm
- Surface Finish
  - Depends on current density and material being machined
  - R_a varies from 0.05 – 12.5 μm
  - New techniques use an oscillating electrode, providing very fine surface finishes.

EDM Applications

Widely used in aerospace, moldmaking, and die casting to produce die cavities, small deep holes, narrow slots, turbine blades, and intricate shapes.



Cavities produced by EDM

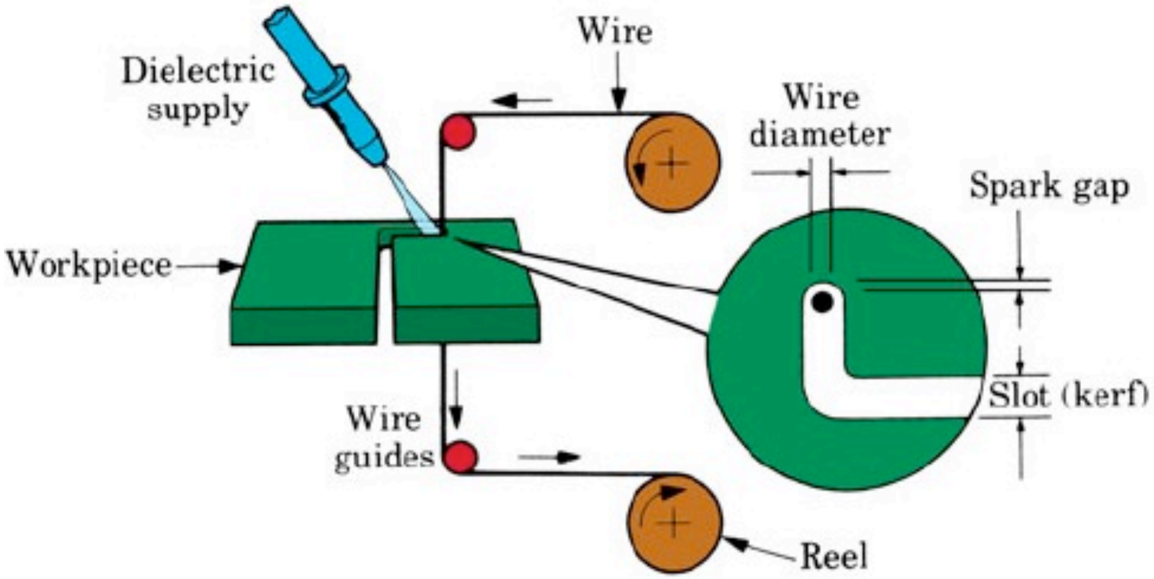


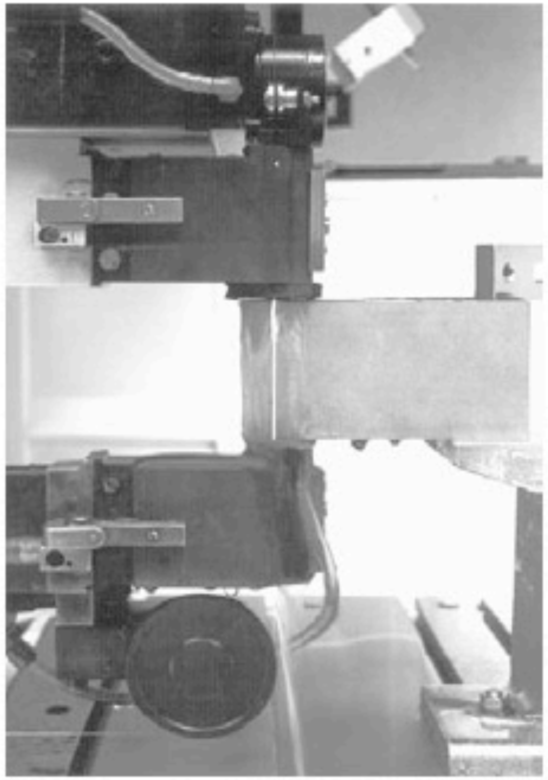
Stepped cavities

EDM Limitations

- Limitations
  - A hard skin, or recast layer is produced which may be undesirable in some cases.
  - Beneath the recast layer is a heat affected zone which may be softer than parent material.
  - Finishing cuts are needed at low MRR.
  - Produces slightly tapered holes, specially if blind.

Wire EDM





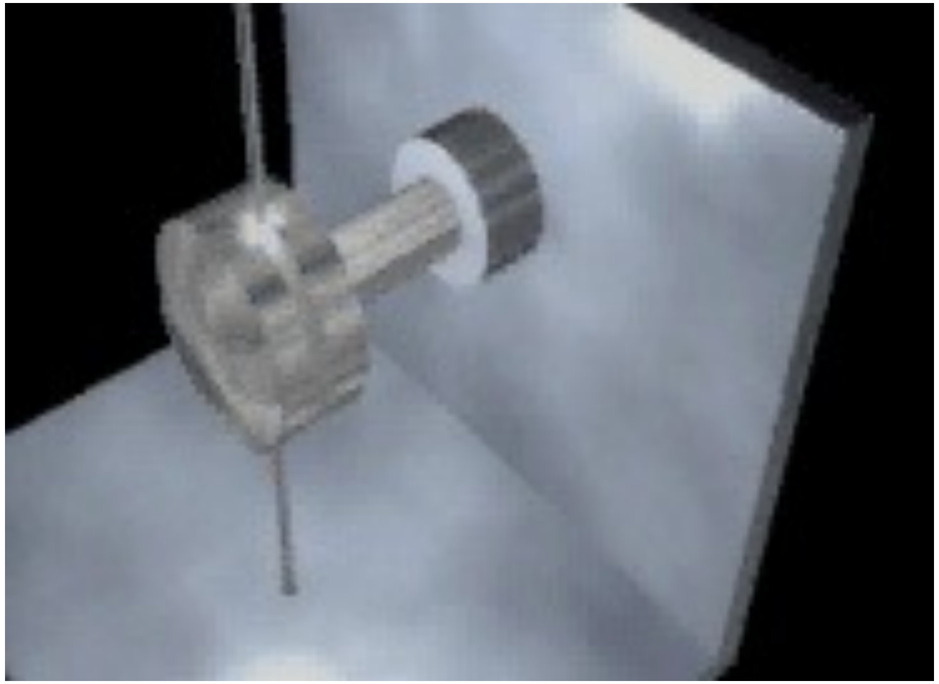
A wire travels along a prescribed path, cutting the workpiece, with the discharge sparks acting like cutting teeth.

Wire EDM (Cont.)

MRR in Wire EDM

$$MRR = V_f \, h \, b$$

$$where,\ b = d_w + 2s$$



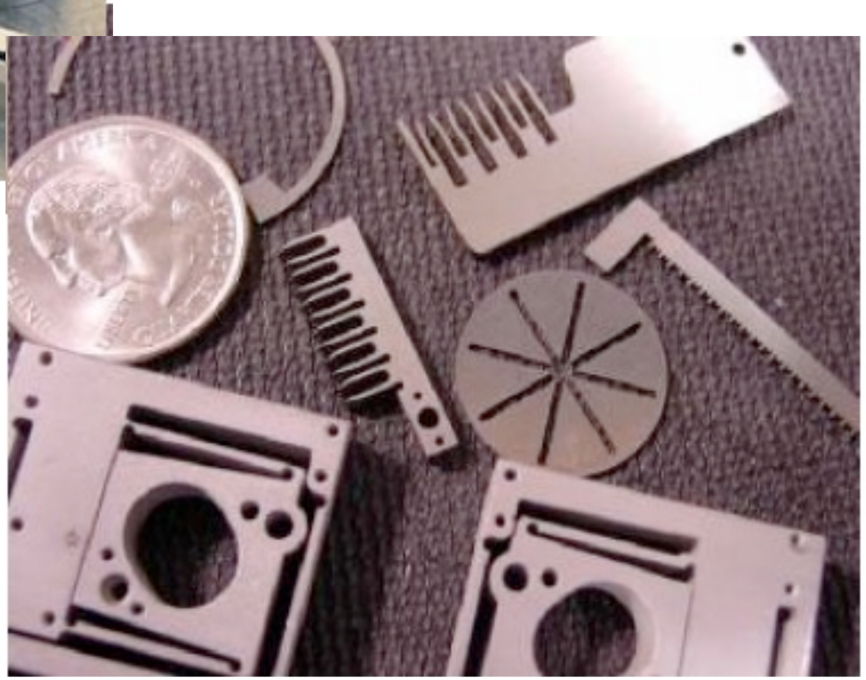
MRR = mm^3/min

V_f = feed rate of wire into the workpiece in mm/min

h = workpiece thickness or height in mm

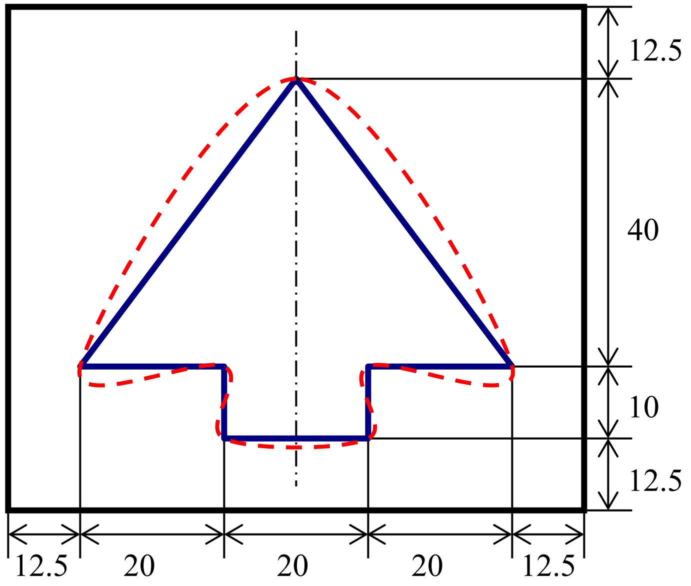
d_w = wire diameter in mm
s = gap between wire and workpiece in mm

Wire EDM Parts



Example

- *Example*: You have to machine the following part from a 85mmx75mmx20mm steel block. You have to choose between EDM and Conventional machining. Your objective is to minimize the cutting power required, which process will you choose?



Assumptions:

- EDM process:
  - Wire diameter: d_w=0.2 mm
  - Gap: s=0.1 mm
- Conventional machining:
  - Negative of the part has to be removed

Example

Solution:

- EDM process

  V_{EDM} = lc*(dw+2s)*t = 1440 mm^3

- Conventional machining

  $V_M = V_{total} – V_{part}$ = 99500 mm^3

- Power comparison

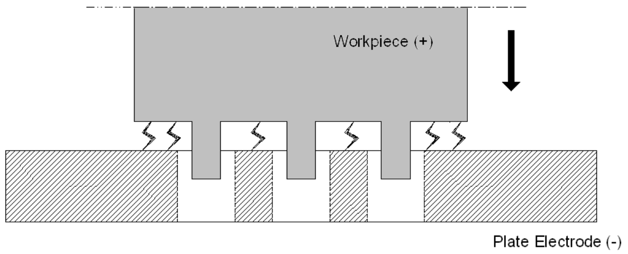
  We will choose machining if $$\frac{u_M V_M}{t_M} \leq \frac{u_{EDM} V_{EDM}}{t_{EDM}}$$

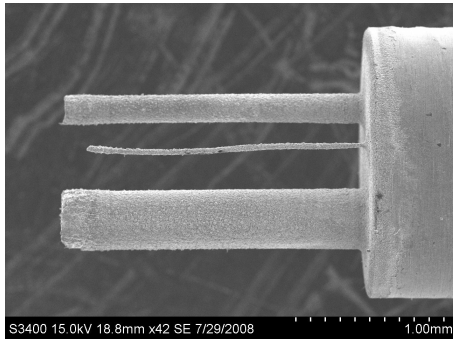
  let's assume $t_{EDM} = \alpha t_M$

  then machining if $$\alpha \leq \frac{u_{EDM} V_{EDM}}{u_M V_M}$$

Reverse micro-EDM

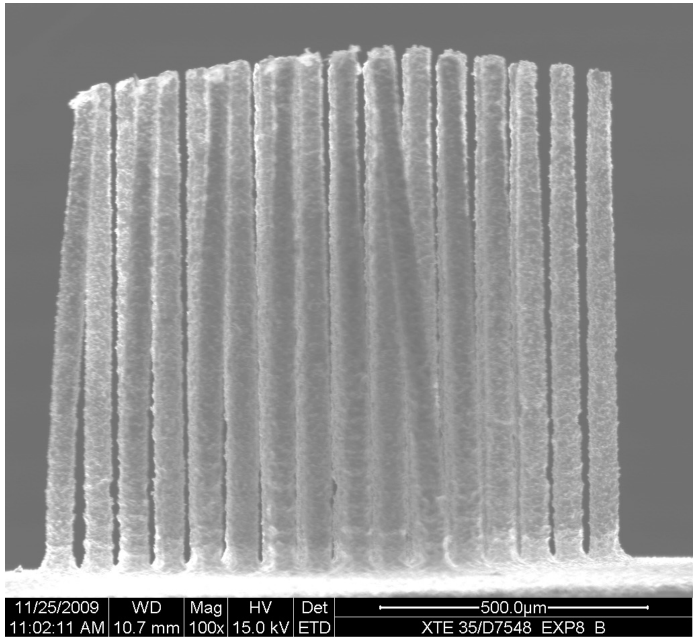
- Fabrication of high aspect ratio micro-electrode arrays



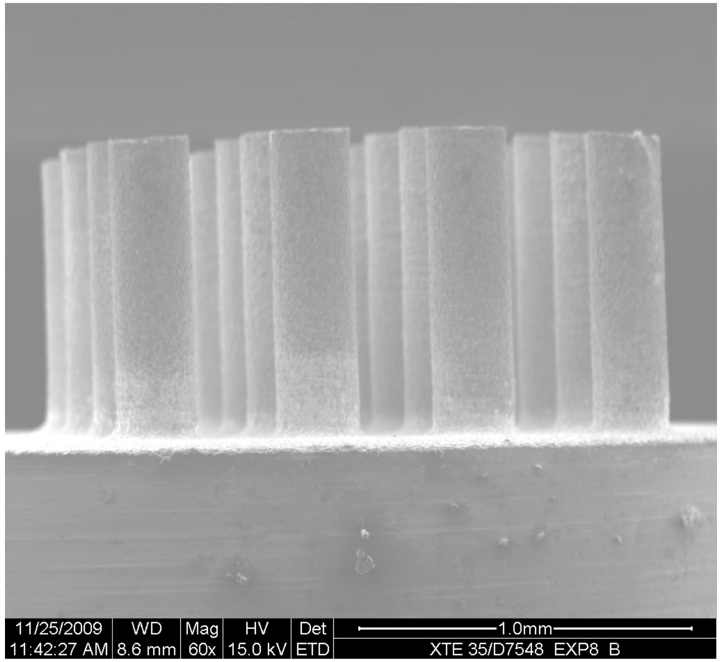


- Potential application in machining hole arrays via micro-EDM/ECM

Arrays Fabricated via R μ-EDM @IITB

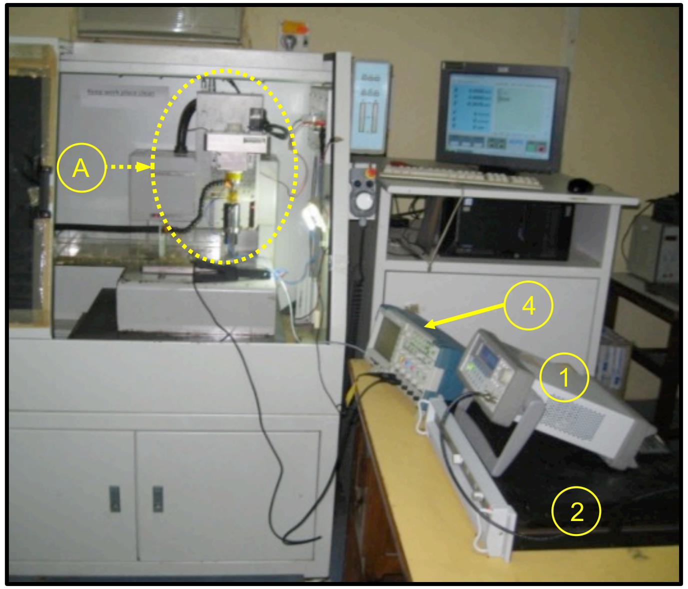


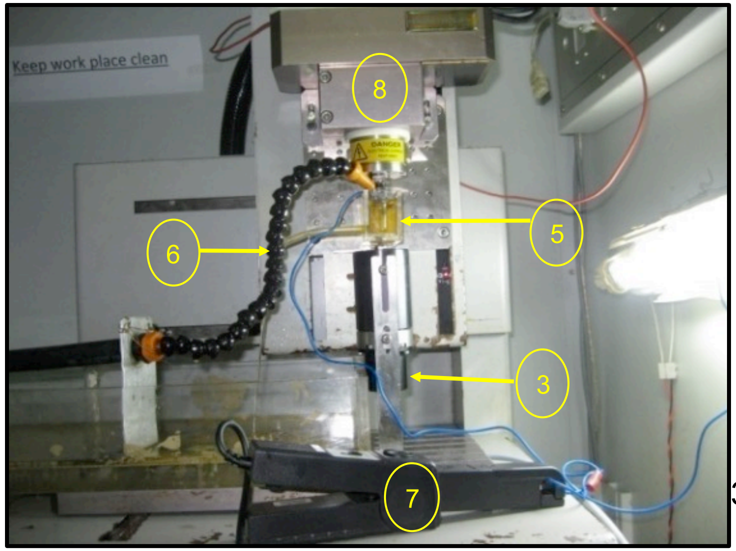
6x6 array



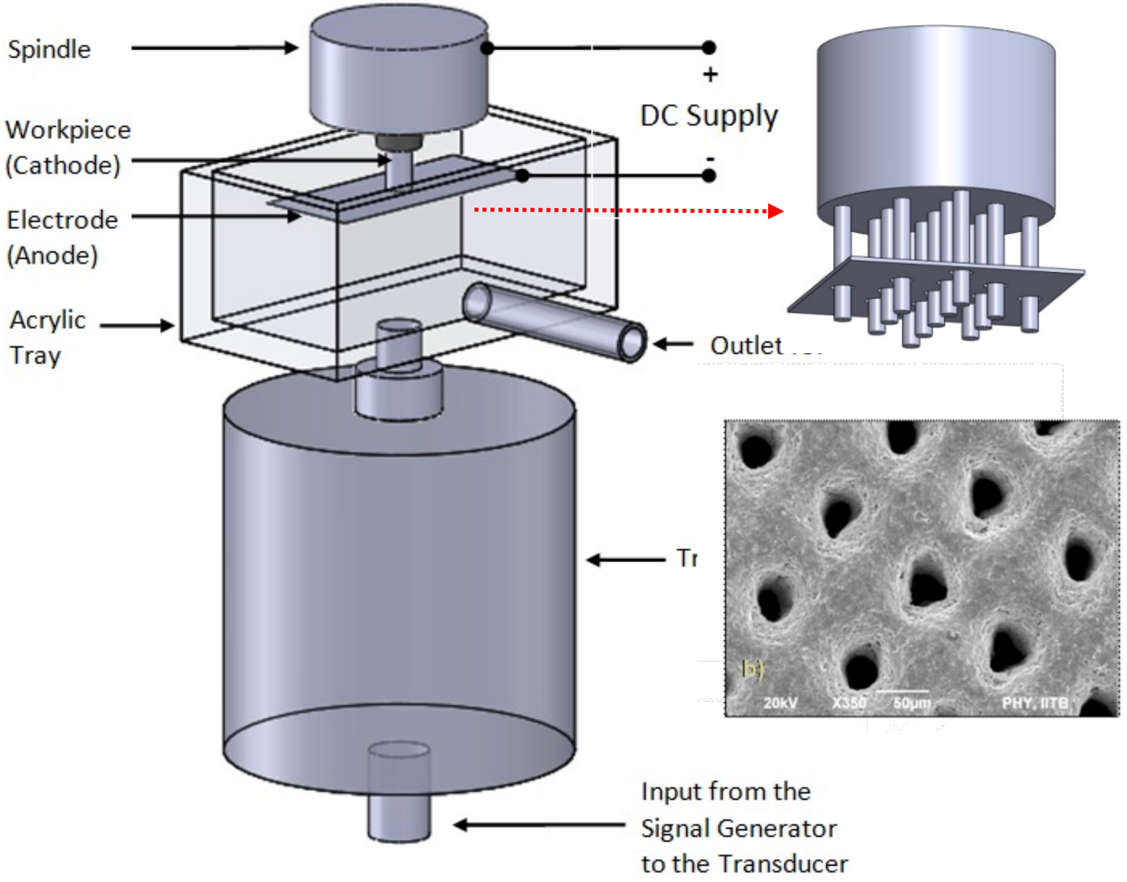
4x4 array

Experimental Setup

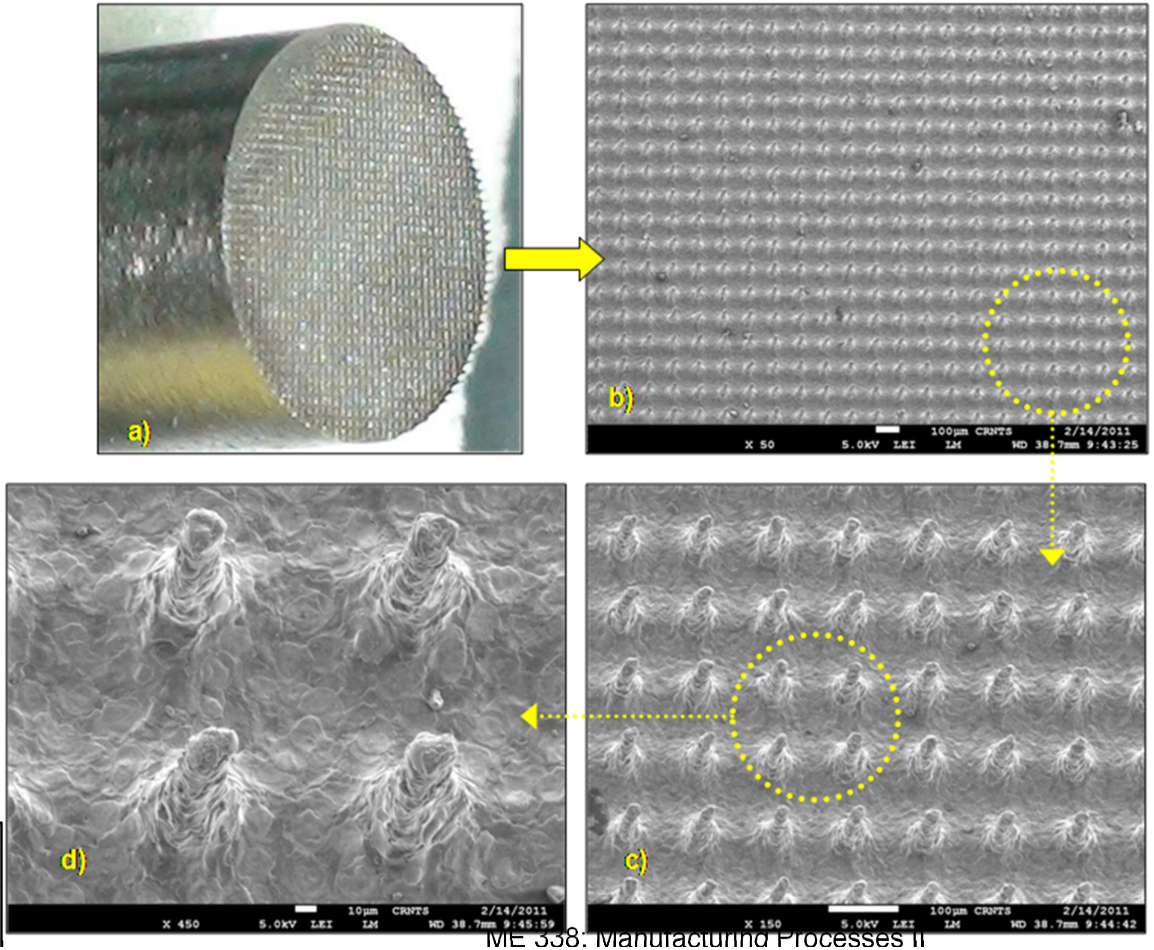




Enlarged view of A

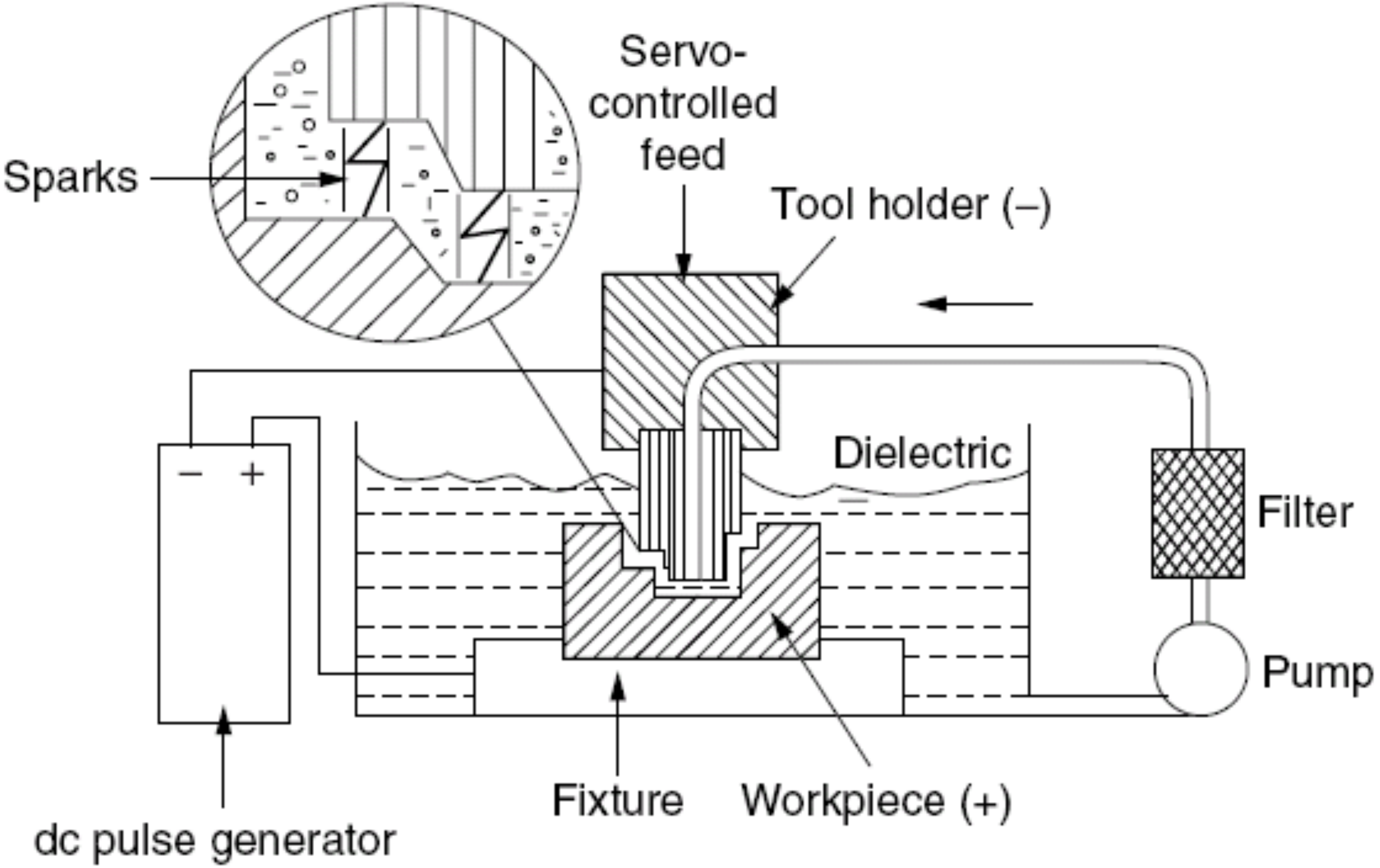


Fabricated Texture



ME 338: Manufacturing Processes II

EDM System

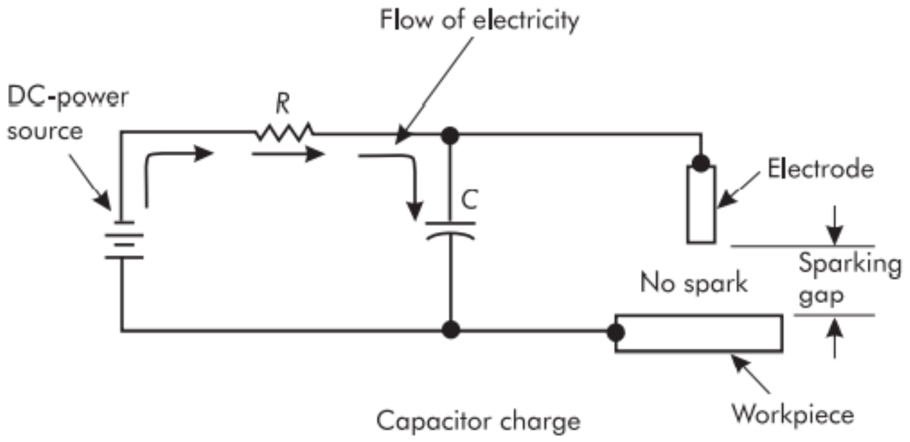


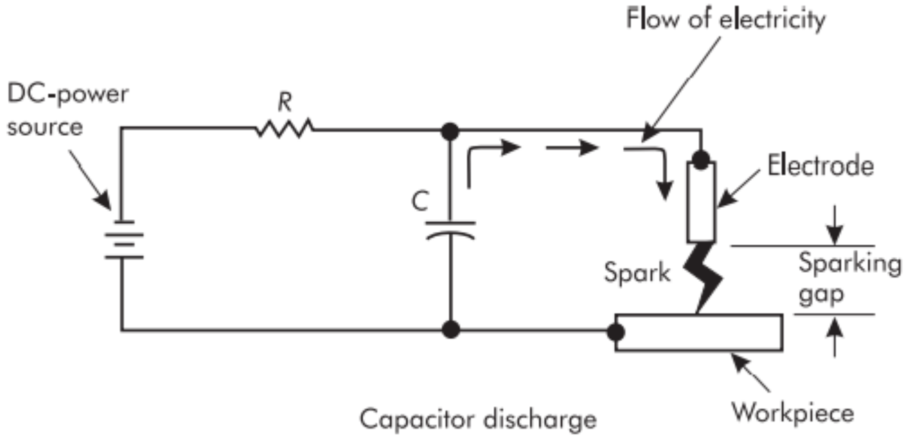
Servo-
controlled
feed
Tool holder (–)
Sparks
Dielectric
Filter
Pump
– +
dc pulse generator
Fixture
Workpiece (+)

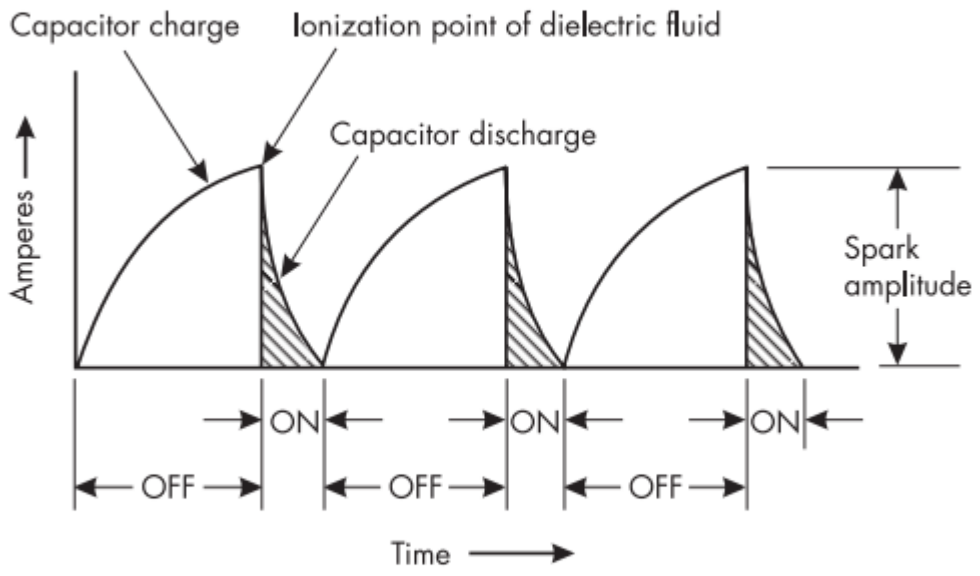
Power Supply System

- Two types of EDM-power supplies:
  - Resistor-capacitor power supply
  - Transistor controlled pulse-power supply
- The sparks produced by the resistor-capacitor (R-C) and the pulse-power supply are quite different and depend on waveform

Resistor-Capacitor (R-C) -Type EDM-Power Supply







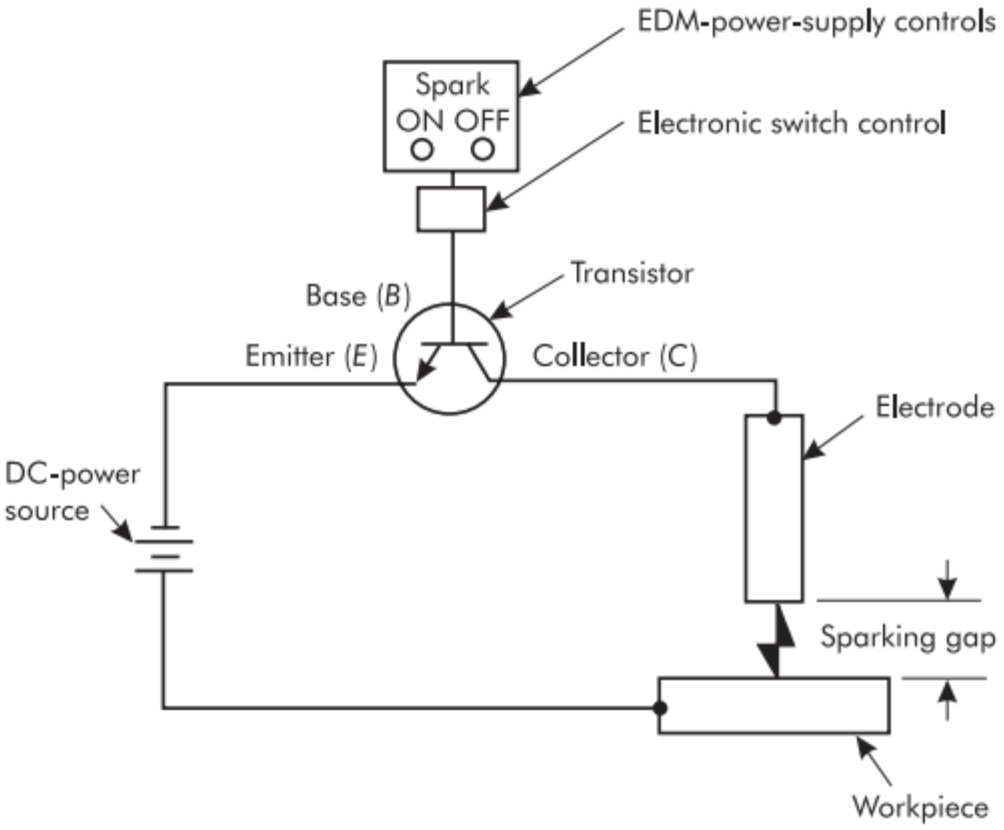
Resistor-Capacitor (R-C) -Type EDM-Power Supply

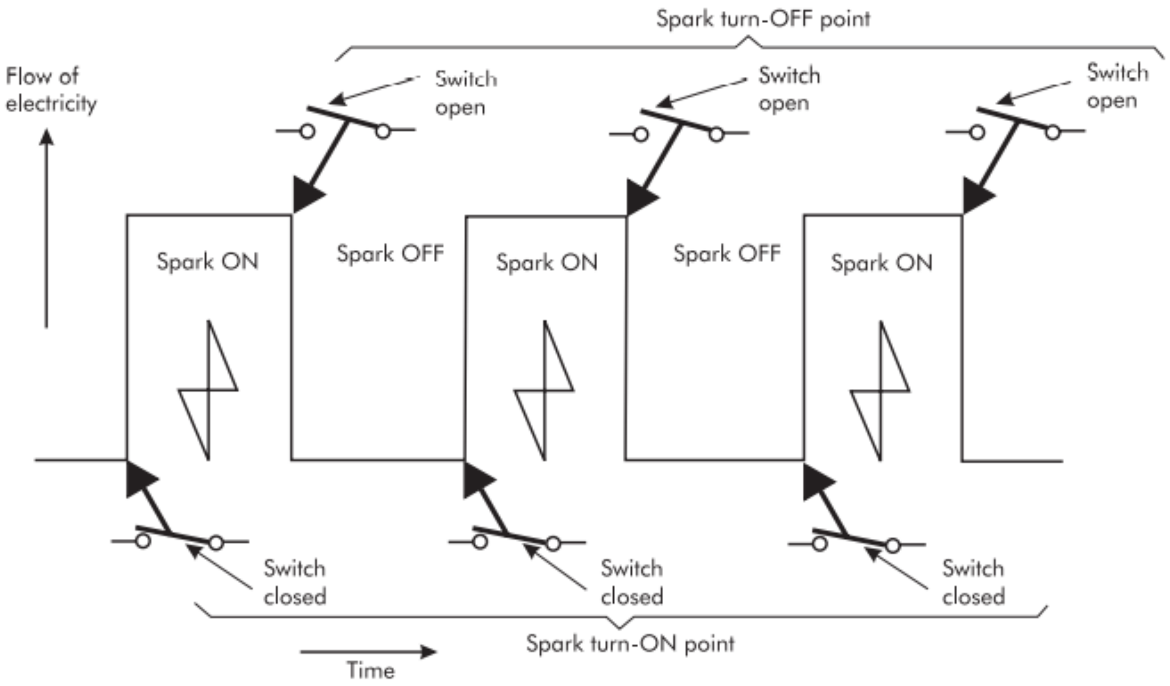
- The main parameters to choose from at setup time are the resistance(s) of the resistor(s) and the capacitance(s) of the capacitor(s)
- In an ideal condition, these quantities would affect the maximum current delivered in a discharge
- Current delivery in a discharge is associated with the charge accumulated on the capacitors at a certain moment
- Little control is expected over the time of discharge, which is likely to depend on the actual spark-gap conditions
- Advantage: RC circuit generator can allow the use of short discharge time more easily than the pulse-controlled generator
- Also, the open circuit voltage (i.e. voltage between electrodes when dielectric is not broken) can be identified as steady state voltage of the RC circuit

Pulse-Power Supply System

- In generators based on transistor control, the user is usually able to deliver a train of voltage pulses to the electrodes
- Each pulse can be controlled in shape, for instance, quasi-rectangular
- In particular, the time between two consecutive pulses and the duration of each pulse can be set
- The amplitude of each pulse constitutes the open circuit voltage
- Thus, maximum duration of discharge is equal to duration of a voltage pulse
- Maximum current during a discharge that the generator delivers can also be controlled

PULSE-POWER-SUPPLY WAVEFORM





Analysis of R-C Circuits

- Charging voltage and charging current:

The charging current (i_{ct}) flowing in charging circuit at time ‘t’ is given by

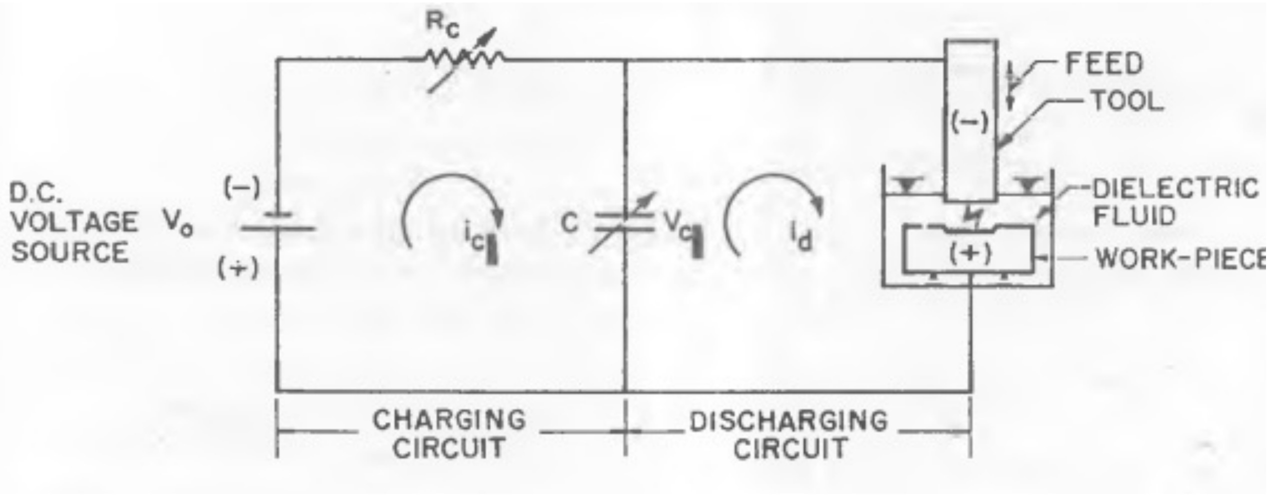
$$i_{ct} = \frac{V_0 - V_{ct}}{R_c} = C\frac{dV_{ct}}{dt}$$

V_0 = supply voltage

V_{ct} = Charged voltage of capacitor

R_c = Charging resistance

C= Capacitance



Analysis of R-C Circuits

$$i_{ct} = \frac{V_0 - V_{ct}}{R_c} = C\frac{dV_{ct}}{dt}$$

Integrating both sides;

$$\ln(V_0 - V_{ct}) = -\frac{t}{R_c C} + K$$

At t=0, $V_{ct} = 0$; K $= \ln(V_0)$

$$V_{ct} = V_0\left(1 - e^{-\frac{t}{R_c C}}\right)$$

$$i_{ct} = \frac{V_0}{R_c}\left(e^{-\frac{t}{R_c C}}\right)$$

Where $R_c C$ is called time constant 'τ'

Power Delivered to the Discharging Circuit

The energy delivered to the discharging circuit at any time t is given by:

$$dE_n = i_{ct}V_{ct}dt = \frac{V_0}{R_c}\left(e^{-\frac{t}{\tau}}\right)V_0\left(1 - e^{-\frac{t}{\tau}}\right)dt$$

Integrating both sides;

$$E_n = \frac{V_0^2}{R_c}\left[-\tau e^{-\frac{t}{\tau}} + \frac{\tau}{2}e^{-2\frac{t}{\tau}}\right] + K'$$

At t=0, $E_n = 0; K' = \frac{V_0^2}{R_c}\frac{\tau}{2}$

$$E_n = \frac{V_0^2\tau}{R_c}\left[\frac{1}{2} - e^{-\frac{t}{\tau}} + \frac{1}{2}e^{-2\frac{t}{\tau}}\right]$$

Power Delivered to the Discharging Circuit

Suppose the energy E_n is delivered to the discharging circuit for time t then the average power delivered (P_{avg}) is given by :

$$P_{avg} = \frac{E_n}{\tau_c} = \frac{V_0^2}{R_c x}\left[\frac{1}{2} - e^{-x} + \frac{1}{2}e^{-2x}\right]$$

Where $x = \frac{t}{\tau}$

The condition for the maximum power to be delivered to the discharging circuit is given by

$$\frac{dP_{avg}}{dx} = 0$$

$$x = 1.26 \quad V_{ct} \approx 0.72V_0$$

Current in the Discharging Circuit

The current (i_d) flowing in discharging circuit at time ‘t’ is given by

$$i_d = \frac{V_{ct}}{R_s} = -C\frac{dV_{ct}}{dt}$$

V_{ct} = Charged voltage of capacitor; R_s = Sparking resistance

C= Capacitance

After integration;

$$\ln(V_{ct}) = -\frac{t}{R_s C} + K''$$

At t=0, $V_{ct} = V_{c0}$; $K'' = \ln(V_{c0})$

$$V_{ct} = V_{c0}e^{-\frac{t}{R_s C}}; \quad i_d = \frac{V_{c0}}{R_s}\left(e^{-\frac{t}{R_s C}}\right)$$

Energy dissipated across the sparking gap is given by $W_d = \frac{1}{2}CV_b^2$ calculate ??

Material Removal rate in RC Circuit

Charged voltage of capacitor $V_{ct} = V_0\left(1 - e^{-\frac{t}{R_cC}}\right)$

$$t_c = R_cC \ln\left(\frac{1}{1 - V_{ct}/V_0}\right)$$

Frequency of charging (f_c) is given by: $f_c = \frac{1}{t_c + t_d} \approx \frac{1}{t_c}$ (why??)

$$f_c = \frac{1}{R_cC}\left[\frac{1}{\ln\left(\frac{1}{1 - V_{ct}/V_0}\right)}\right]$$

Material Removal rate in RC Circuit

Material removal rate should be proportional to the total energy delivered in the sparking per second:

$$MRR \propto \frac{1}{2} C V_b^2 f_c$$

$$MRR = K_1 C V_b^2 \frac{1}{R_c C} \left[\frac{1}{\ln\left(\frac{1}{1 - V_{ct}/V_0}\right)} \right]$$

$$MRR \propto \frac{1}{R_c}$$

Surface Finish

- In EDM, each spark results in approximately spherical crater formation on the surface of the workpiece
- Hence, the center line average (H) value of surface finish will be a function of crater depth (h) and frequency of sparking (f_c)

$$H \propto \frac{h}{f_c}$$

- The volume of the material removed $(\propto\ h^3)$ per discharge will be proportional to the energy delivered during sparking $(= CV_b^2/2)$. Hence, $h^3 \propto CV_b^2$

$$h \propto C^{1/3} V_b^{2/3}$$

$$H \propto \frac{C^{1/3} V_b^{2/3}}{f_c}$$

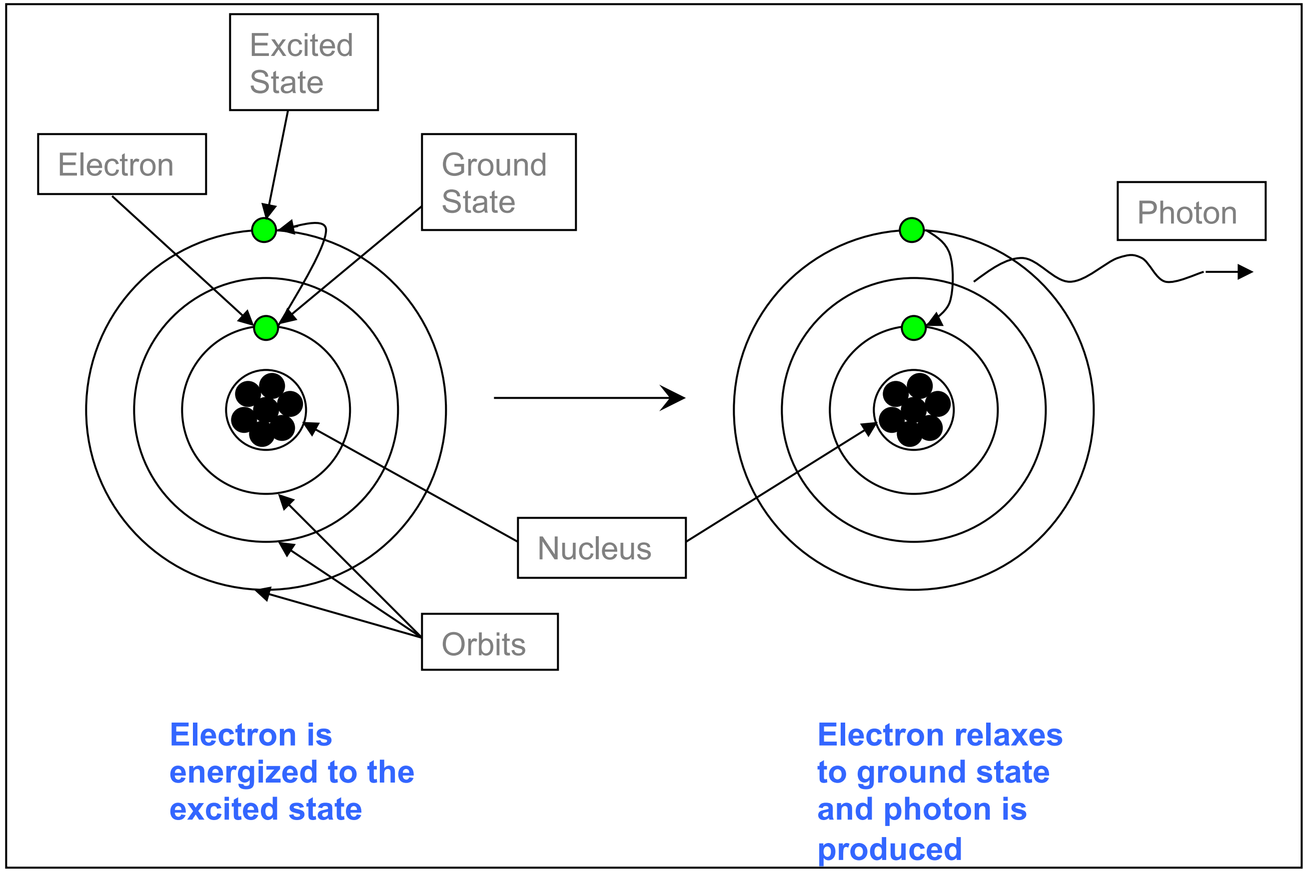
High-Energy-Beam Machining

- Laser-Beam Machining (LBM)
- Electron-Beam Machining (EBM)
- Focused Ion-Beam Machining

Laser-Beam Machining (LBM)

- Laser Concept
  - Add energy to make electrons “jump” to higher energy orbit
  - Electron “relaxes” and moves to equilibrium at ground-state energy level
  - Emits a photon in this process (key laser component)
  - Two mirrors reflect the photons back and forth and “excite” more electrons
  - One mirror is partially reflective to allow some light to pass through: creates narrow laser beam

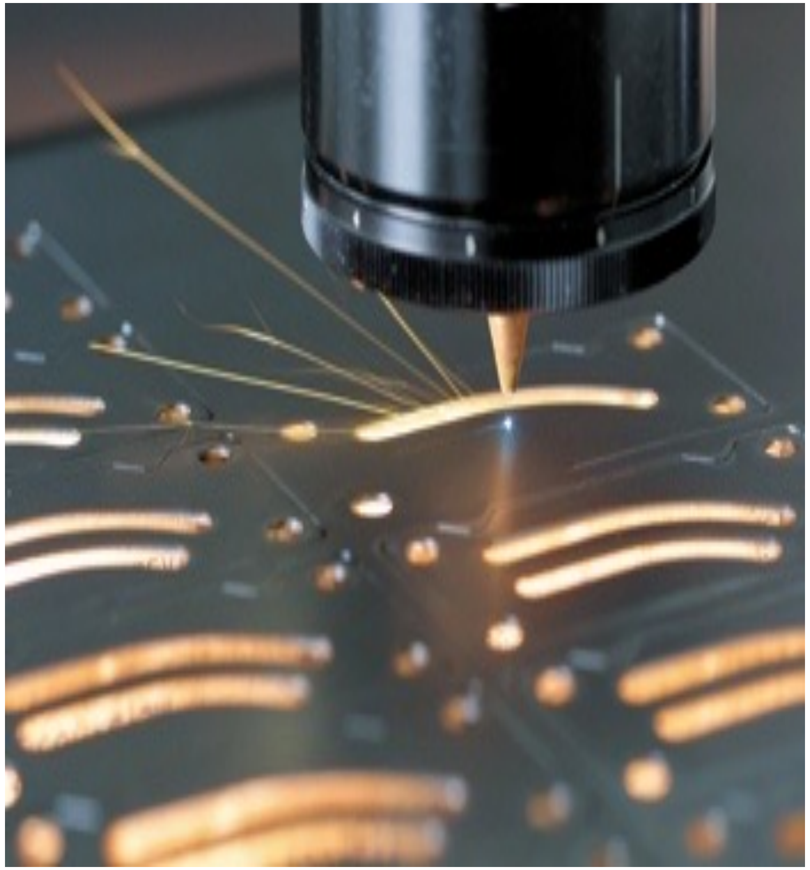
LBM (Cont.)



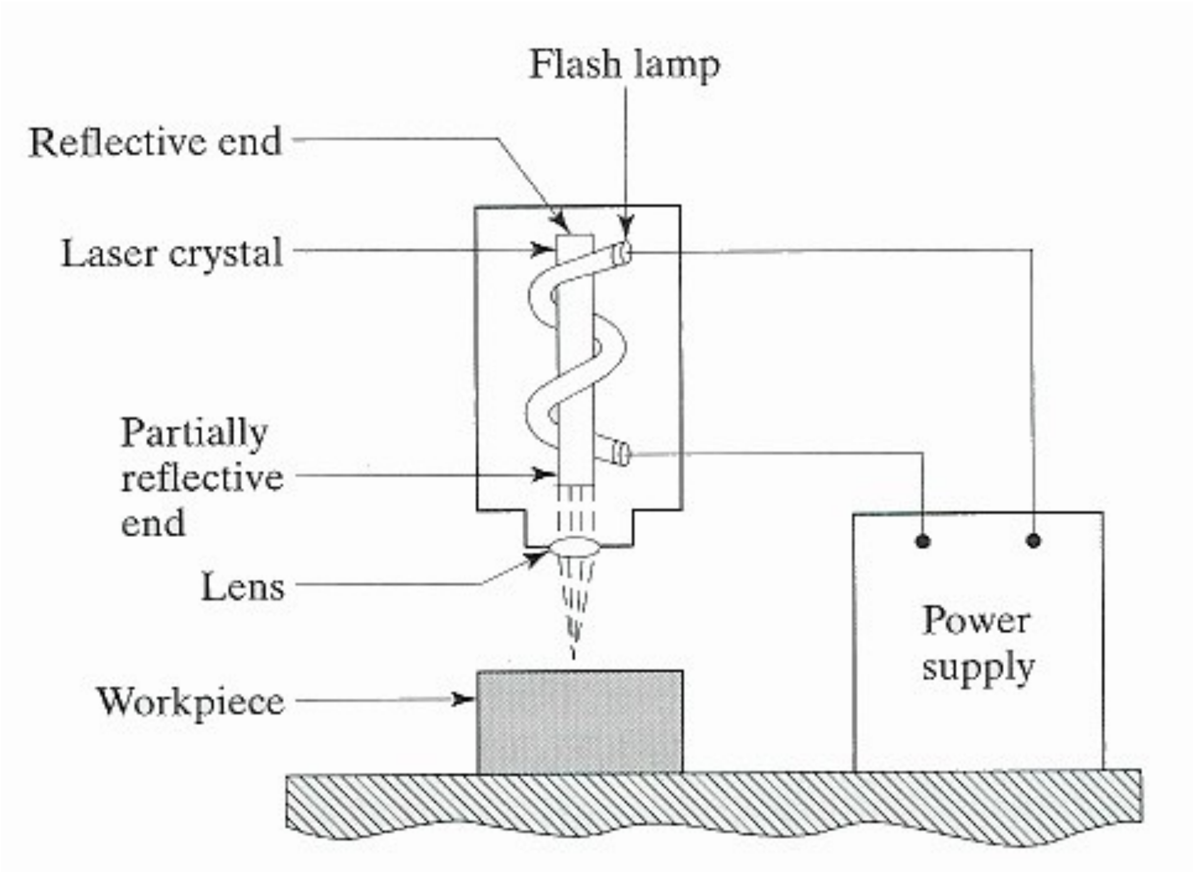
Photon Emission Model

LBM (Cont.)

- More precise
- Useful with a variety of materials: metals, composites, plastics, and ceramics
- Smooth, clean cuts
- Faster process
- Decreased heat-affected zone

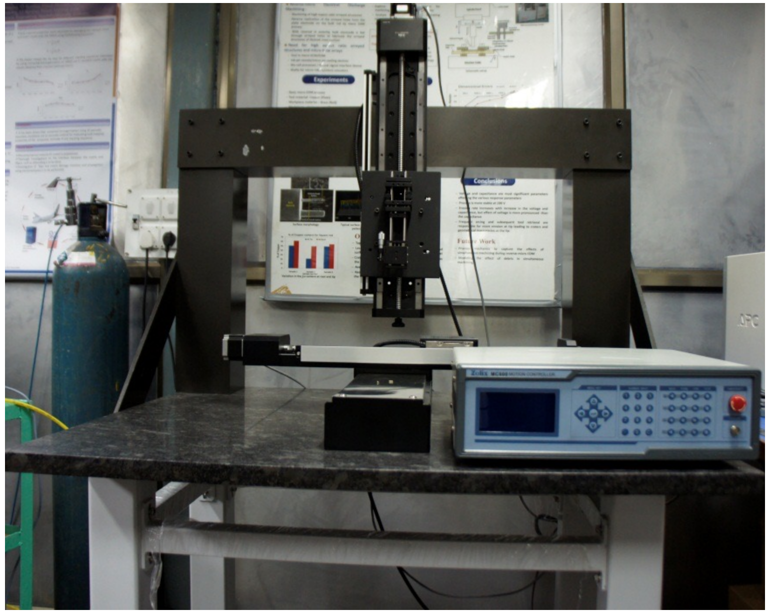


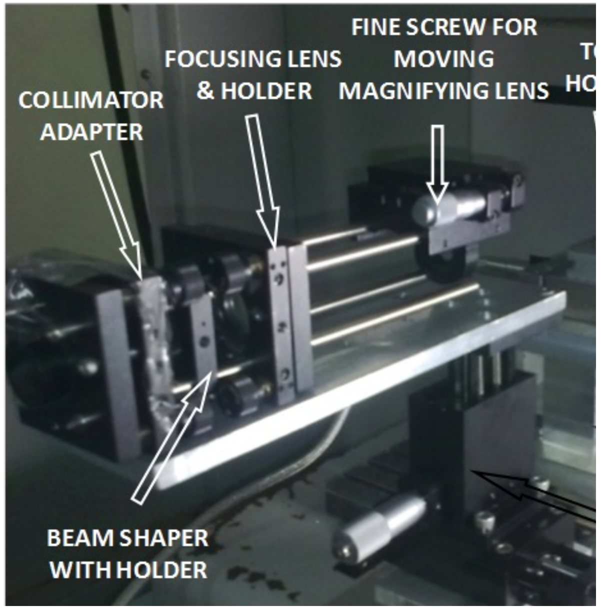
Schematic of LBM Device



Laser Setup

- Laser Processing Center
  - 100 W SPI single mode fiber laser (Power and frequency modulated)
  - Optics for variable intensity distribution and spot size
  - 3 axis (Z decoupled) translational stages and controls





  - Provides uniform/Gaussian intensity
  - 7 μm -900 μm spot size possible
  - Hardening/Cladding/Texturing/Brazing

"Method and device for generating laser beam of variable intensity distribution and variable spot size",
Indian Patent Application No. 442/MUM/2011.

LBM (Cont.)

- Important physical parameters in LBM
  - Reflectivity
  - Thermal conductivity of workpiece surface
  - Specific heat and latent heats of melting and evaporation
- The lower these quantities, the more efficient the process.
- The cutting depth *t*: $t \propto \frac{P}{d\,V}$

P is the power input, v is the cutting speed, and d is the laser-beam-spot diameter.

LBM Capability

- MRR
  - Cutting speed can be as high as 4 m/min.
  - Typical material removal rate is 5 mm^3/min.

- Dimensional Tolerance
  - Typical ranges from $\pm$0.015 - $\pm$0.125 mm

- Surface Finish
  - R_a varies between 0.4 – 6.3 μm.

LBM (Cont.)

- Process Variations
  - Laser beam machines can be used for cutting, surface hardening, welding, drilling, blanking, engraving and trimming.
  - Types of lasers used: pulsed and CW CO_2, Nd:YAG, Nd:glass, ruby and excimer.
  - High-pressure gas streams are used to enhance the process by aiding the exothermic reaction process, to cool and blow away the vaporized or molten material and slag.

LBM (Cont.)

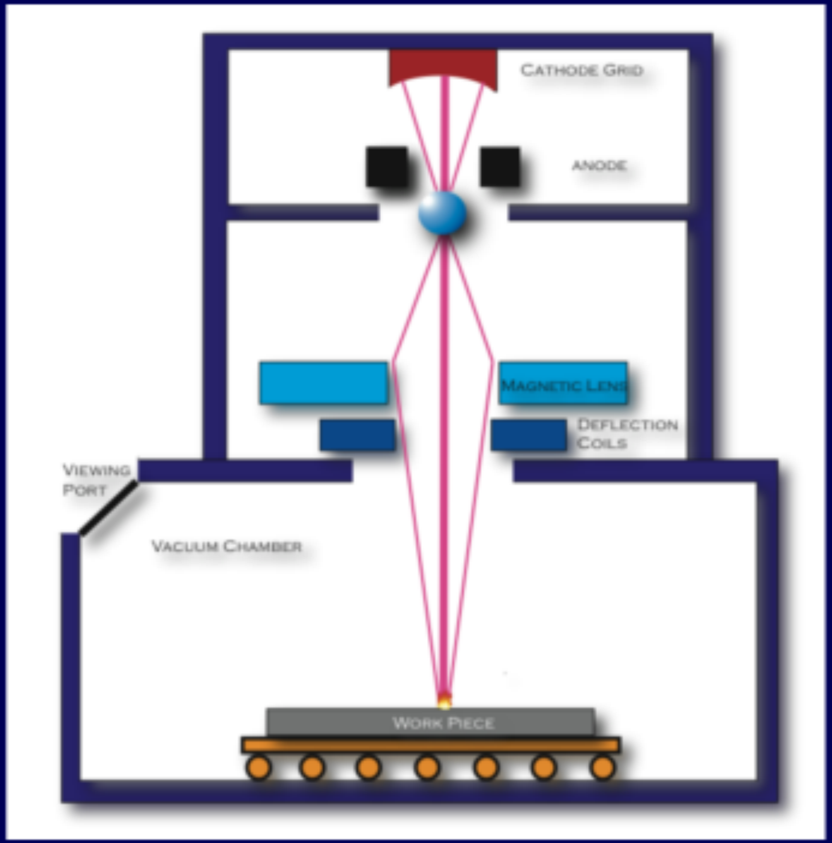
- Applications
  - Multiple holes in very thin and thick materials
  - Non-standard shaped holes and slots
  - Prototype parts
  - Trimming, scribing and engraving of hard materials
  - Small diameter lubrication holes

- Limitations
  - Localized thermal stresses, heat affected zones, recast layer and thermal distribution in thin parts
  - Difficulty of material processing depends on how close materials boiling and melting points are
  - Hole wall geometry can be irregular
  - The cutting of flammable materials is usually inert gas assisted

Electron-Beam Machining (EBM)

How it Works

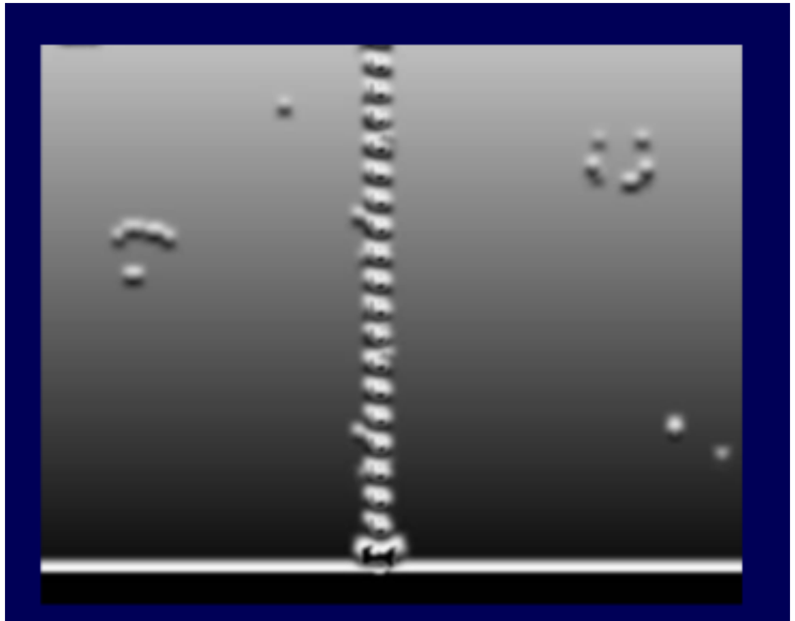
- A stream of electrons is started by a voltage differential at the cathode. The concave shape of the cathode grid concentrates the stream through the anode.
- The anode applies a potential field that accelerates the electrons.
- The electron stream is then forced through a valve in the electron beam machine.
- The beam is focused onto the surface of the work material, heating, melting, and vaporizing the material.

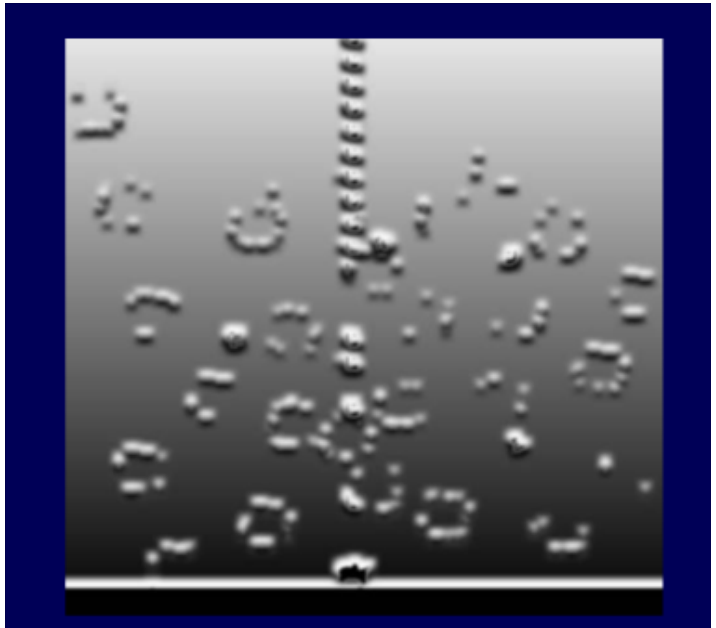


Schematic Illustration of Electron-Beam Machining Process

EBM (Cont.)

The entire process occurs in a vacuum chamber because a collision between an electron and an air molecule causes the electrons to veer off course. LBM doesn’t need vacuum because the size and mass of a photon is numerous times smaller than the size of an electron.


Electron-Beam in a Vacuum


Electron Beam in Ambient Air

EBM Characteristics

- Mechanics of material removal – melting, vaporization
- Medium – vacuum
- Tool – beam of electrons moving at very high velocity
- Maximum MRR = 10 mm^3/min
- Specific power consumption = 450 W/mm^3/min
- Critical parameters – accelerating voltage, beam diameter, work speed, melting temperature
- Materials application – all materials
- Shape application – drilling fine holes, cutting contours in sheets, cutting narrow slots
- Limitations – very high specific energy consumption, necessity of vacuum, expensive machine

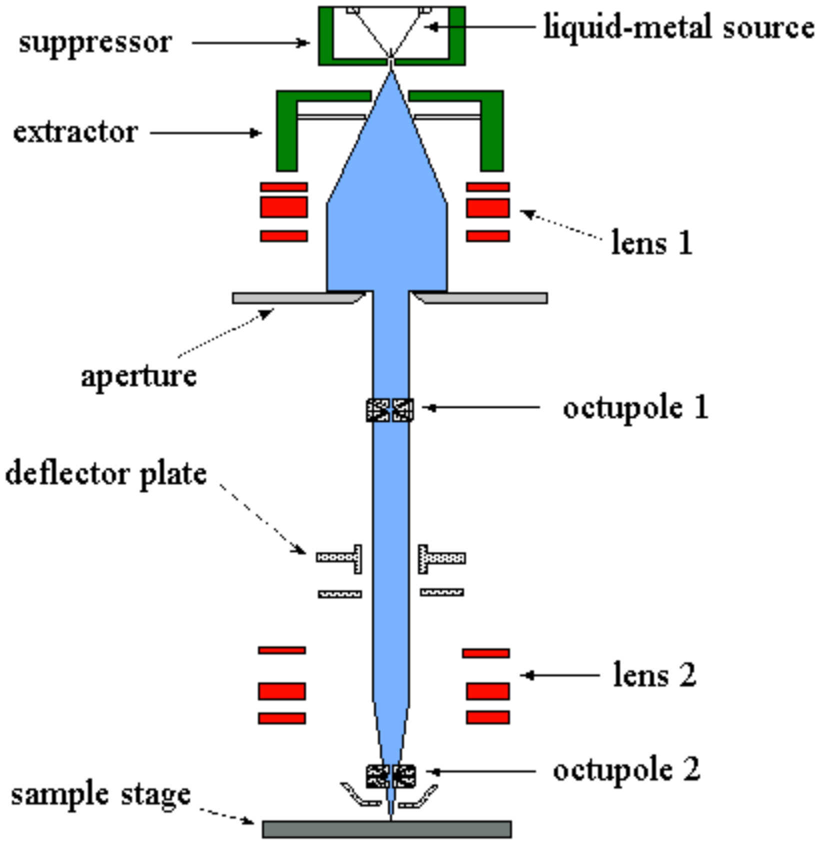
Comparative Performance

Process	Metal removal rate (cm^3/s)	Approximate unit power (specific cutting energy) (GJ/m^3)	Relative capital equipment cost per unit material removal rate
Edge-tool machining	14	3	1
Abrasive machining	8	30	2
Plasma jet	1.5	10	—
ECM	1.0	500	60
EDM	0.10	150	40
Ultrasonic machining	0.005	150	600
Electron beam	0.001	1,500	40,000
Abrasive jet	0.0001	10,000	—
Laser	0.0001	150,000	160,000

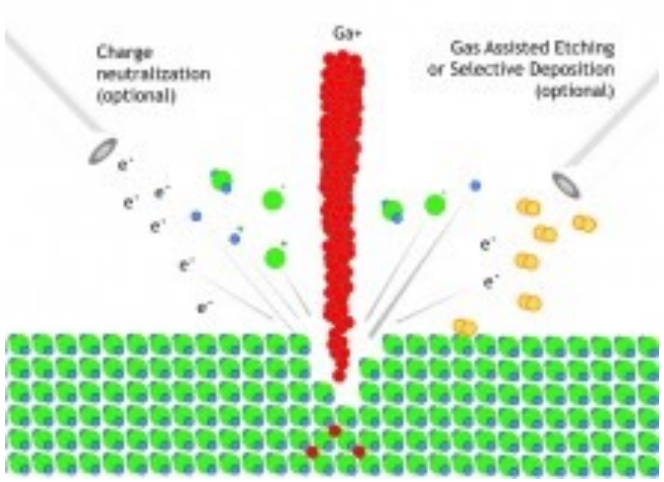
[a]Adapted from Wager [18].

Focused Ion Beam Technologies

- Ga^+ ion beam raster over the surface similar to SEM
- Milling of small holes and modifications in the structures can be done
- Most instruments combine nowadays a SEM and FIB for imaging with high resolution, and accurate control of the progress of the milling
- Process is performed in vacuum



Mechanism



Rate of etch depth

$$\frac{dz}{dt} = \frac{YM}{A\rho}\left(\frac{I}{e}\right)$$

Where, Y is sputter yield of surface atoms per incoming ion, using a probe of current I is given by A is the etched area, ρ is the density of target material, M is atomic mass of target material and e is charge

Dual Beam System

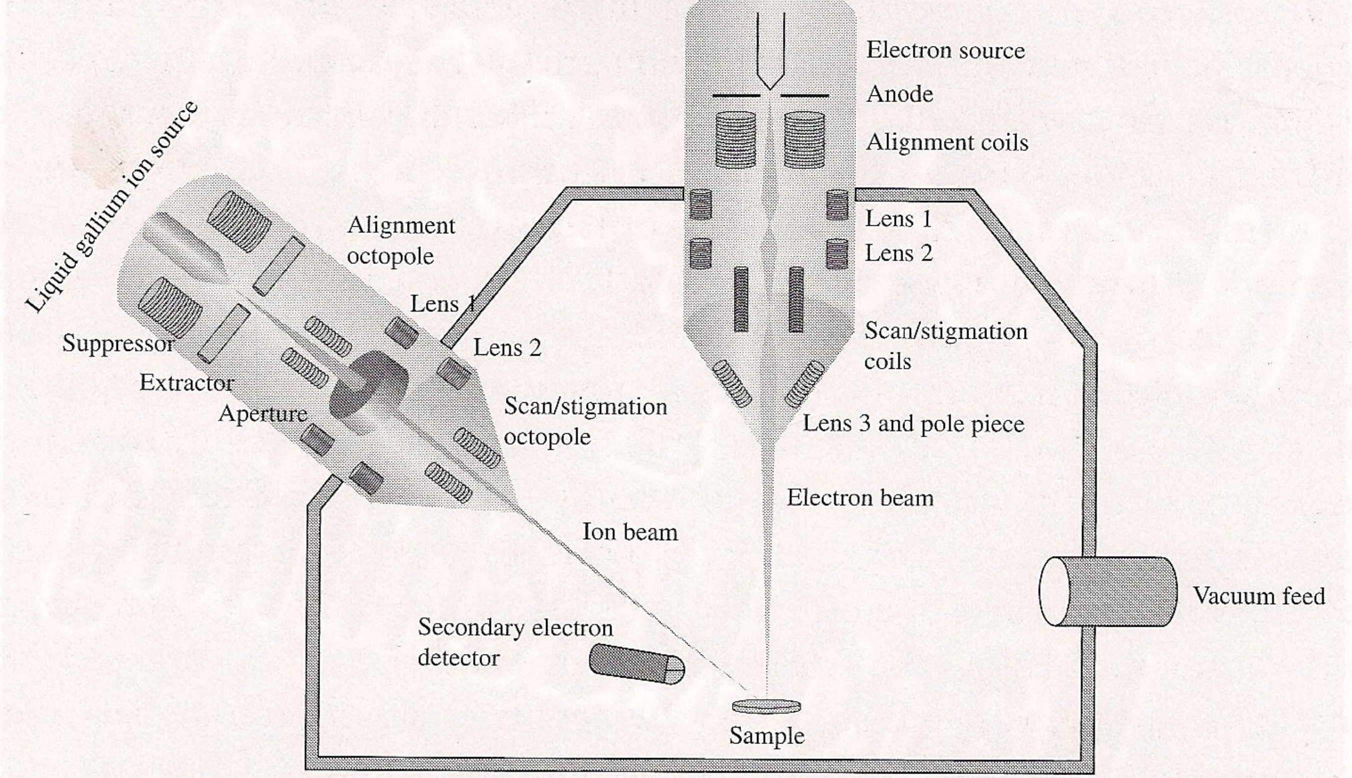


Figure 1.2 A schematic diagram showing the configuration of a two-beam focused ion beam system.

Table 1.1 *Quantitative comparison of FIB ions and SEM electrons*

Particle	FIB	SEM	Ratio
Type	Ga^+ ion	Electron	
Elementary charge	+1	−1	
Particle size	0.2 nm	0.00001 nm	20 000
Mass	1.2×10^{-25} kg	9.1×10^{-31} kg	130 000
Velocity at 30 kV	2.8×10^{5} m/s	1.0×10^{8} m/s	0.0028
Velocity at 2 kV	7.3×10^{4} m/s	2.6×10^{7} m/s	0.0028
Velocity at 1 kV	5.2×10^{4} m/s	1.8×10^{7} m/s	0.0028
Momentum at 30 kV	3.4×10^{-20} kg m/s	9.1×10^{-23} kg m/s	370
Momentum at 2 kV	8.8×10^{-21} kg m/s	2.4×10^{-23} kg m/s	370
Momentum at 1 kV	6.2×10^{-21} kg m/s	1.6×10^{-23} kg m/s	370
Beam			
Size	nm range	nm range	
Energy	up to 30 kV	up to 30 kV	~
Current	pA to nA range	pA to µA range	~
Penetration depth			
In polymer at 30 kV	60 nm	12000 nm	0.005
In polymer at 2 kV	12 nm	100 nm	0.12
In iron at 30 kV	20 nm	1800 nm	0.11
In iron at 2 kV	4 nm	25 nm	0.16
Average signal per 100 particles at 20 kV			
Secondary electrons	100–200	50–75	1.33–4.0
Backscattered electron	0	30–50	0
Substrate atom	500	0	infinite
Secondary ion	30	0	infinite
X-ray	0	0.7	0

Focused Ion Beam Technologies

- FIB finds application in:
  - Ablation of hard materials: diamond, WC
  - Polishing of single crystals
  - Deposition
  - Site-specific analysis
  - FIB lithography
  - TEM samples

- Capital investment ~ 5 Crore

Process Capabilities of FIB

- Deposition
- Etching
- Low material removal
- Very high cost
- Nanometric imaging resolution
- Can process conducting and non conducting materials

Summary

- Process description and capability
  - Ultrasonic Machining (USM)
  - Water-Jet Machining & Abrasive-Jet Machining
  - Chemical Machining
  - Electrochemical Machining (ECM)
  - Electrical-Discharge Machining (EDM)
- High-Energy-Beam Machining
  - Laser-beam machining (LBM)
  - Electron-beam machining (EBM)
  - Focused Ion Beam (FIB)