Introduction to Non-Traditional Machining

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Non-Traditional Machining

- Traditional machining is mostly based on removal of materials using tools that are harder than the materials themselves.
- New and novel materials because of their greatly improved chemical, mechanical and thermal properties are sometimes impossible to machine using traditional machining processes.
- Traditional machining methods are often ineffective in machining hard materials like ceramics and composites or machining under very tight tolerances as in micromachined components.
- The need to a avoid surface damage that often accompanies the stresses created by conventional machining.

Example: aerospace and electronics industries.

- They are classified under the domain of non traditional processes.

Classification of Non-Traditional Machining

These can be classified according to the source of energy used to generate such a machining action: mechanical, thermal, chemical and electrochemical.

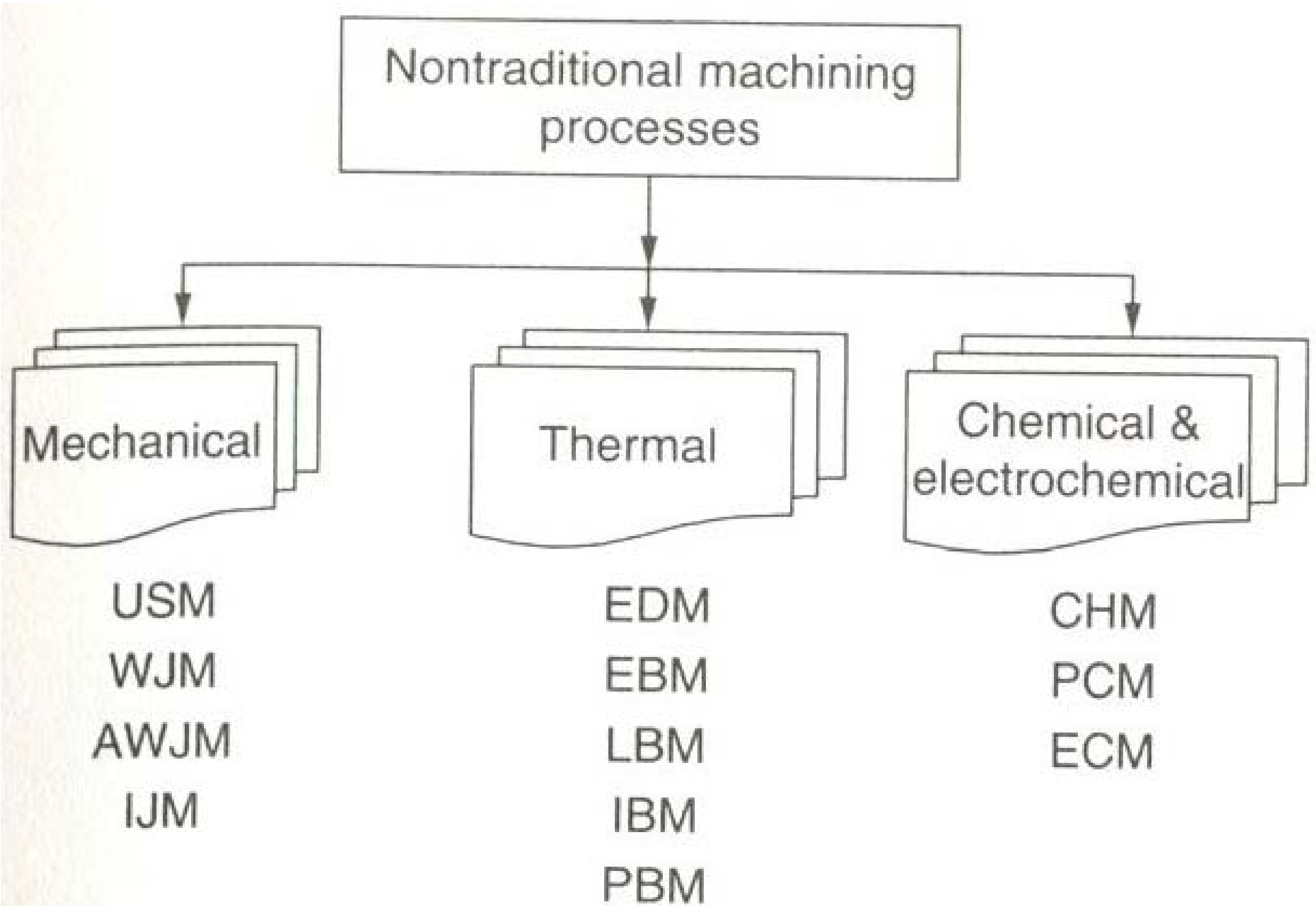
Mechanical: Erosion of the work material by a high velocity stream of abrasives or fluids (or both)

Thermal: The thermal energy is applied to a very small portion of the work surface, causing that portion to be removed by fusion and/or vaporization of the material. The thermal energy is generated by conversion of electrical energy.

Electrochemical: Mechanism is reverse of electroplating.

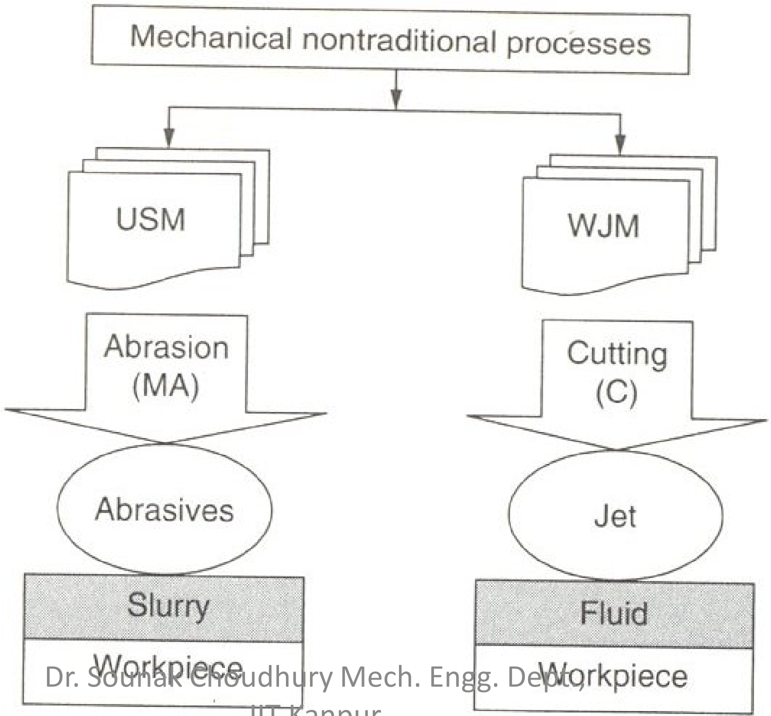
Chemical: Most materials (metals particularly) are susceptible to chemical attack by certain acids or other etchants. In chemical machining, chemicals selectively remove material from portions of the workpart, while other portions of the surface are protected by a mask.

Classification of Non-Traditional Machining

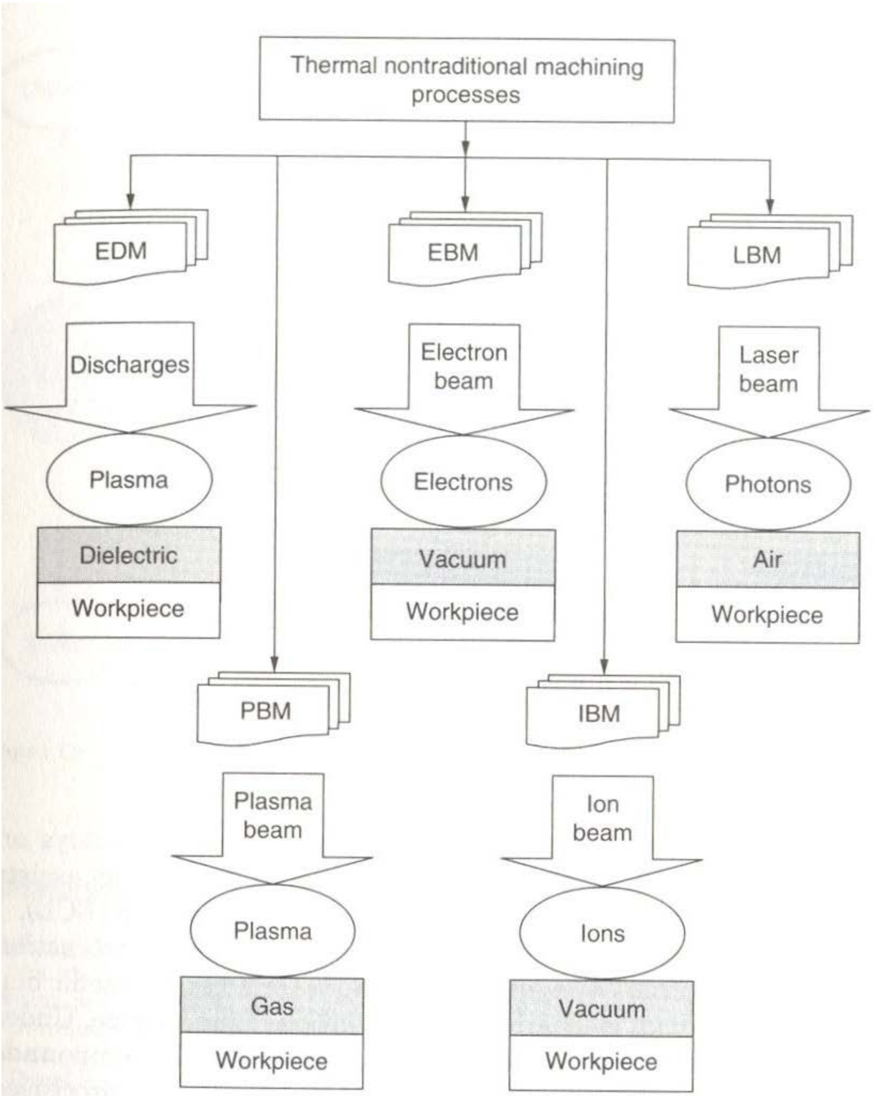


Mechanical Machining

- Ultrasonic Machining (USM) and Waterjet Machining (WJM) are typical examples of single action, mechanical non traditional machining processes.
- The machining medium is solid grains suspended in an abrasive slurry in the former, while a fluid is employed in the WJM process.
- The introduction of abrasives to the fluid jet enhances the machining efficiency and is known as abrasive water jet machining. Similar case happens when ice particles are introduced as in Ice Jet Machining.

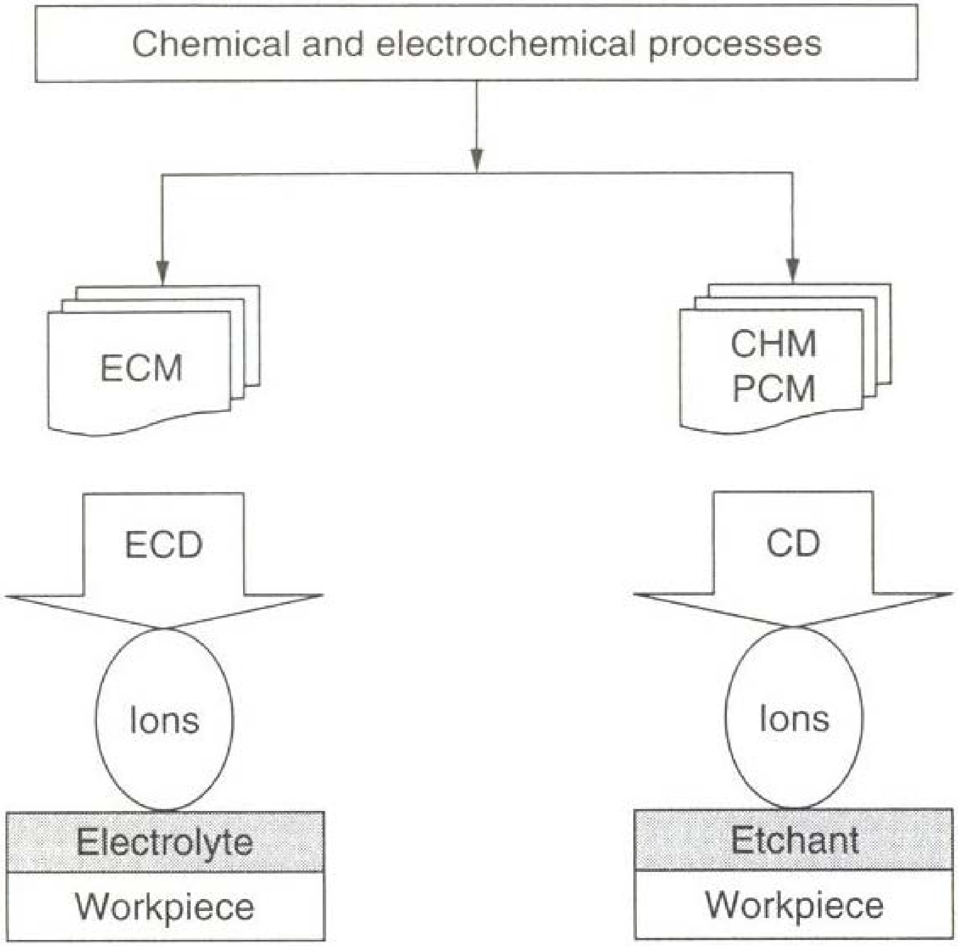


Thermal Machining



- Thermal machining removes materials by melting or vaporizing the work piece material.
- Many secondary phenomena occur during machining such as microcracking, formation of heat affected zones, striations etc.
- The source of heat could be plasma as during EDM and PBM or photons as during LBM, electrons in EBM, ions in IBM etc.

Chemical and Electrochemical Machining

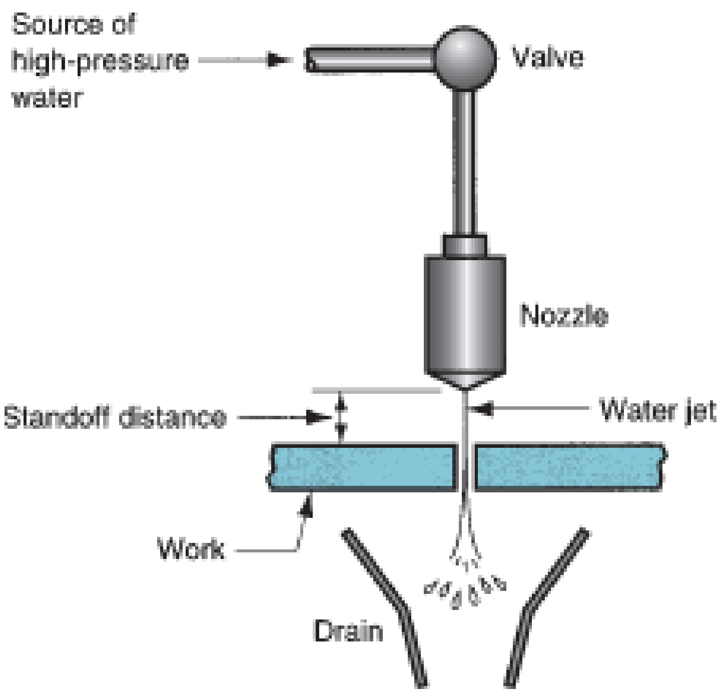


- Chemical milling and photochemical machining or photochemical blanking all use a chemical dissolution action to remove the machining allowance through ions in an etchant.
- Electrochemical machining uses the electrochemical dissolution phase to remove the machining allowance using ion transfer in an electrolytic cell.

Water Jet Cutting (WJC)

- Also known as hydrodynamic machining.
- Uses a fine, high-pressure, high-velocity of water directed at the work surface to cause cutting of the work.

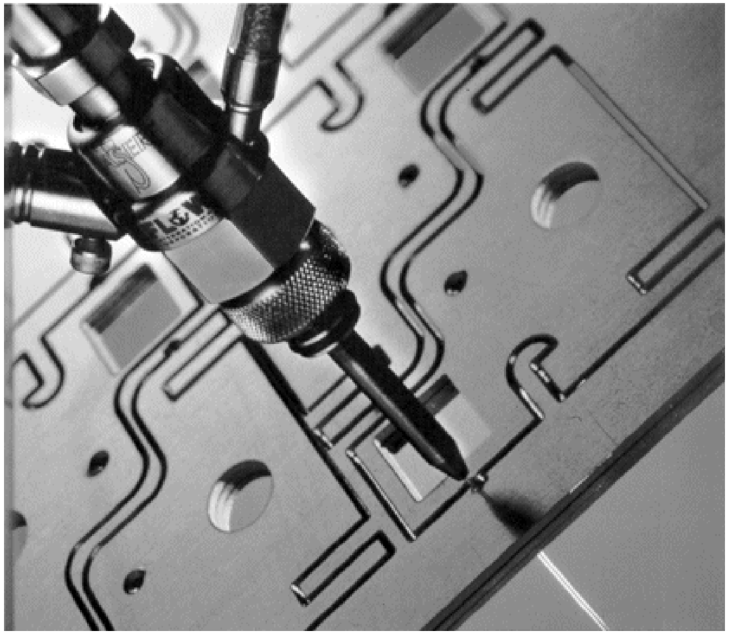
- Nozzle diameter: 0.1 to 0.4 mm
- Pressure: up to 400 MPa
- Velocity: up to 900 m/s
- Fluid is pressurized by a hydraulic pump



Important process parameters

- Standoff distance: small to avoid dispersion of the fluid stream (3.2 mm)
- Nozzle opening diameter: affects precision
- Water pressure: high for thicker materials
- Cutting feed rate: the velocity at which the WJC nozzle is traversed along the cutting path

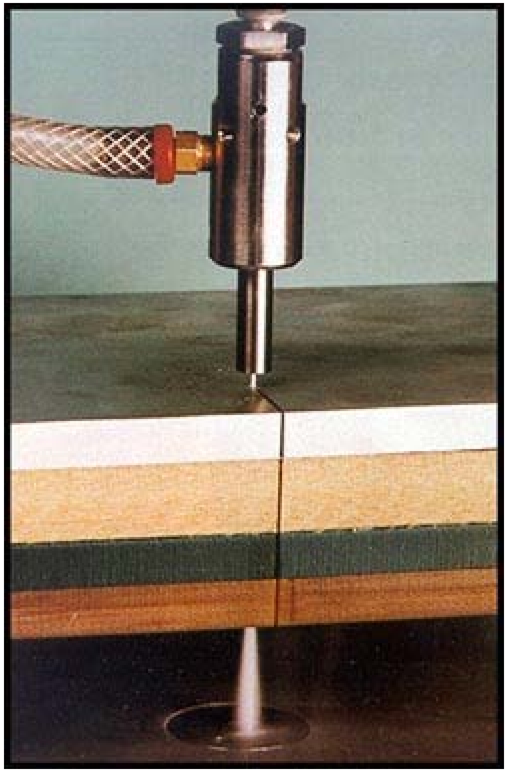
Water Jet Machining



A fine (0.1 – 0.4 mm dia.), high pressure (400 MPa), high velocity (900 m/s) stream of water is directed at the work surface to cause cutting.

Used for: Plastic, Textile, Composites, Tile, Carpet, Leather and Cardboard

Water Jet Machining



Complex shapes can be machined using CNC WJC

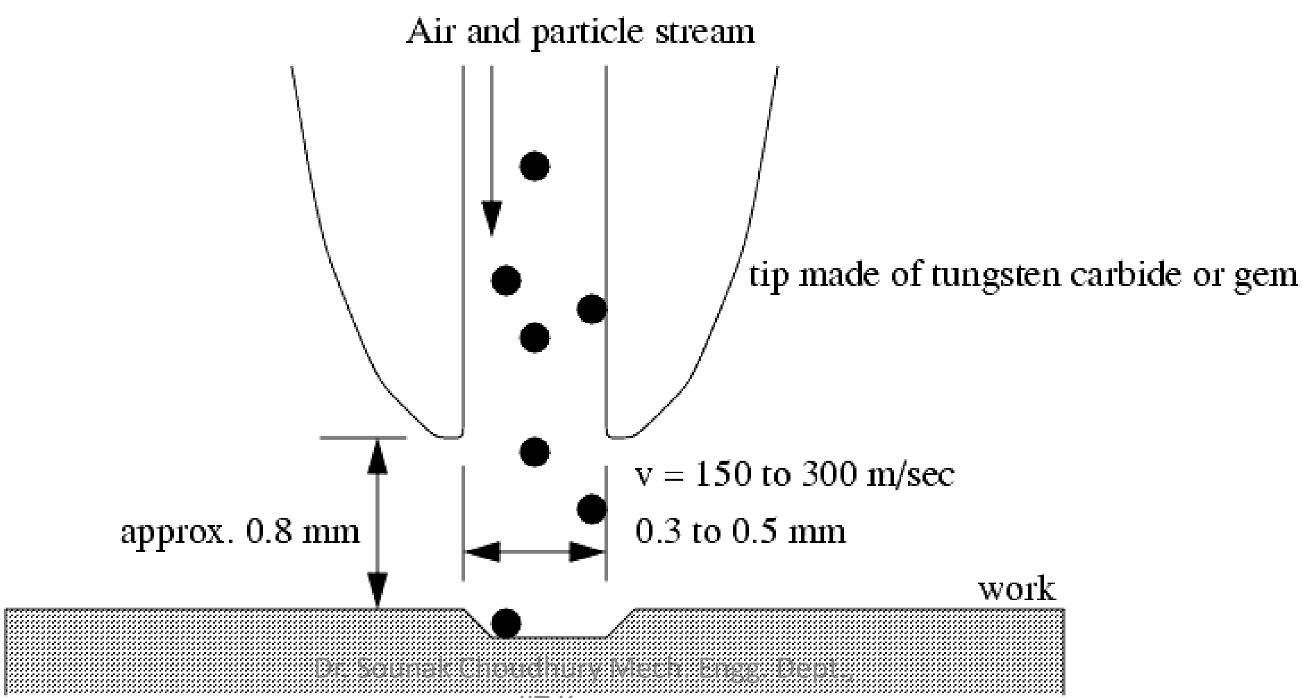
WJC Applications

- Usually automated by CNC or industrial robots to manipulate nozzle along desired trajectory
- Used to cut narrow slits in flat stock such as plastic, textiles, composites, floor tile, carpet, leather, and cardboard
- Not suitable for brittle materials (e.g., glass)

- **WJC advantages:** no crushing or burning of work surface, minimum material loss, no environmental pollution, and ease of automation

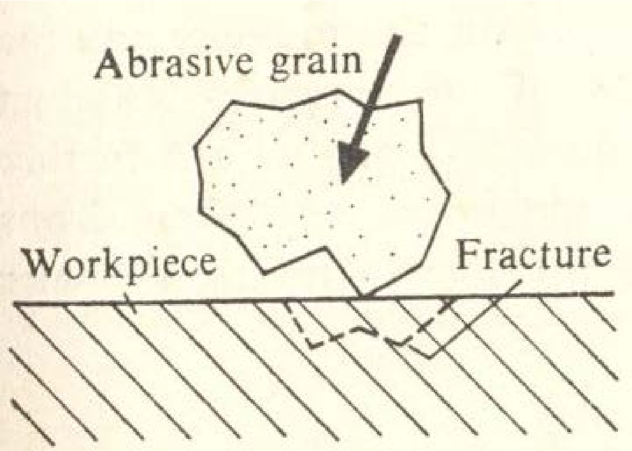
Introduction to Abrasive Jet Machining (AJM)

- In AJM, the material removal takes place due to impingement of the fine abrasive particles.
- The abrasive particles are typically of 0.025 mm diameter and the air discharges at a pressure of several atmosphere.

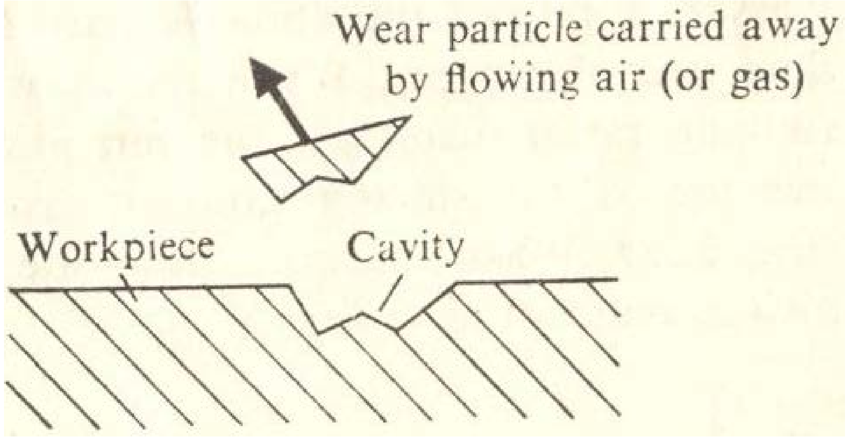


Mechanics of AJM

- Abrasive particle impinges on the work surface at a high velocity and this impact causes a tiny brittle fracture and the following air or gas carries away the dislodged small work piece particle.
- The process is more suitable when the work material is brittle and fragile.



Fracture of work surface



Formation of cavity

Process Parameters of AJM

- The process characteristics can be evaluated by judging

  (1) the MRR,

  (2) the geometry of the cut,

  (3) the roughness of the surface produced, and

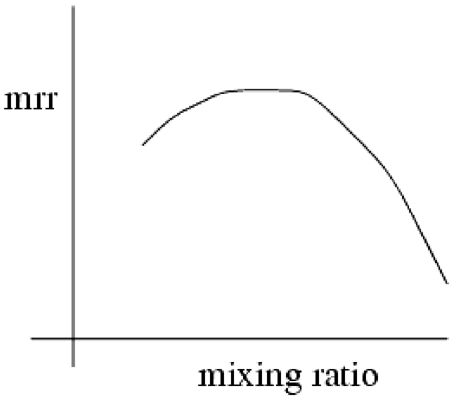
  (4) the rate of nozzle wear.

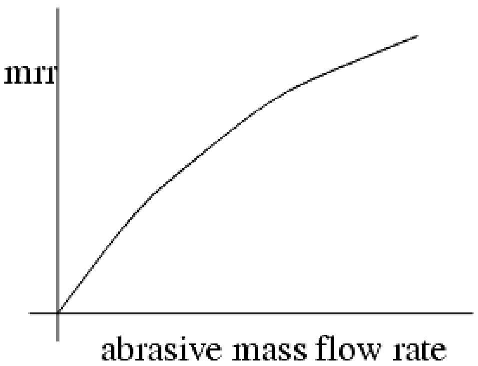
- The major parameters which control these quantities are:

  1. The abrasive (composition, strength, size and mass flow rate).
  2. The gas (composition, pressure and velocity).
  3. The nozzle (geometry, material, distance from and inclination to the work surface).

The Abrasive

- Mainly two types of abrasives are used (1) Aluminum oxide and (2) Silicon carbide. (Grains with a diameter 10-50 microns are readily available)
- For good wear action on the surfaces, the abrasive grains should have sharp edges.
- A reuse of the abrasive powder is normally not recommended because of a decrease of cutting capacity and clogging of the nozzle orifices due to contamination.
- The mass flow rate of the abrasive particles depends on the pressure and the flow rate of the gas.





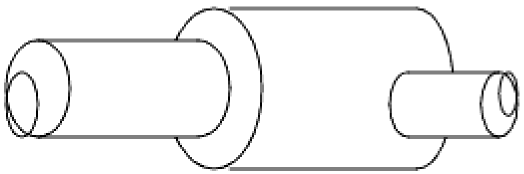
- There is an optimum mixing ratio (mass fraction of the abrasive in the jet) for which the metal removal rate is the highest.
- When the mass flow rate of the abrasive increases the material removal rate also increases.

The Gas

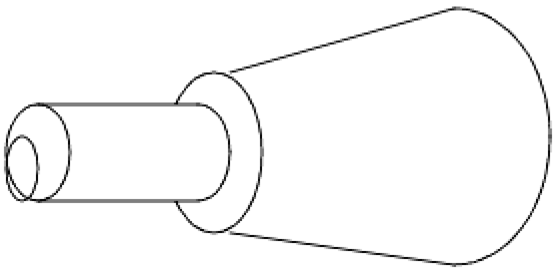
- The AJM unit normally operates at a pressure of 0.2-1.0 N/mm^2 .
- The composition of gas and a high velocity has a significant impact on the MRR even if the mixing ratio is not changed.

The Nozzle

- The nozzle is one of the most vital elements controlling the process characteristics.
- The nozzle material should be hard to avoid any significant wear due to the flowing abrasive. [Normally WC (avg. life: 12-30 hrs.) or Sapphire (Appr. = 300 hrs.) are used]
- For a normal operation the cross-sectional area of the orifice can be either circular or rectangular and between 0.05- 0.2mm^2 .



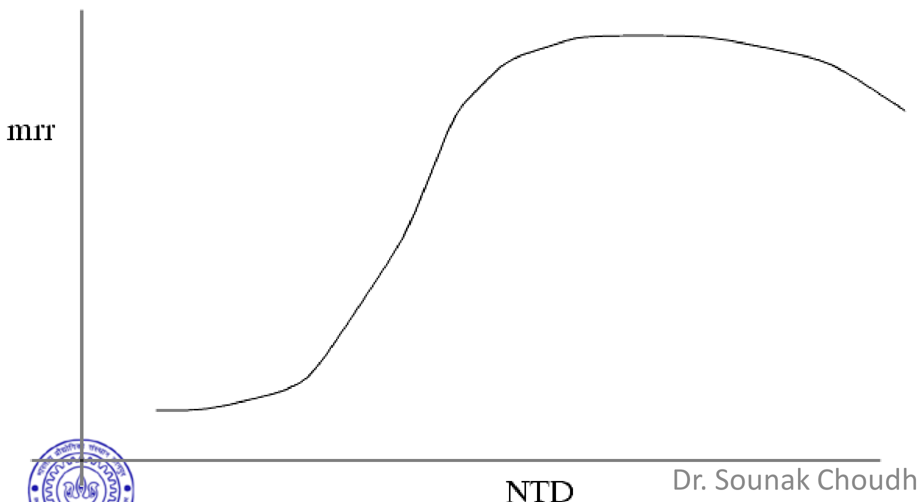
right angled head

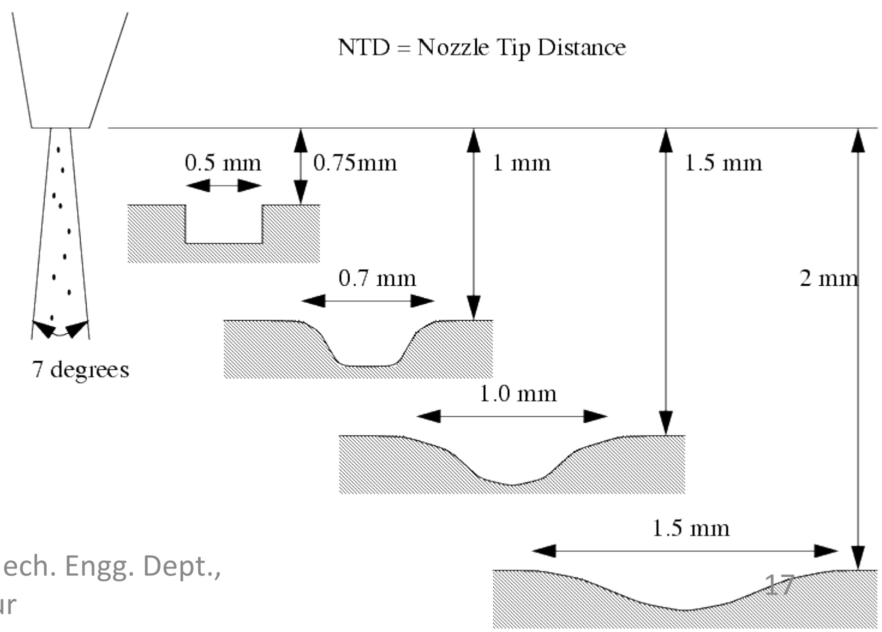


straight head

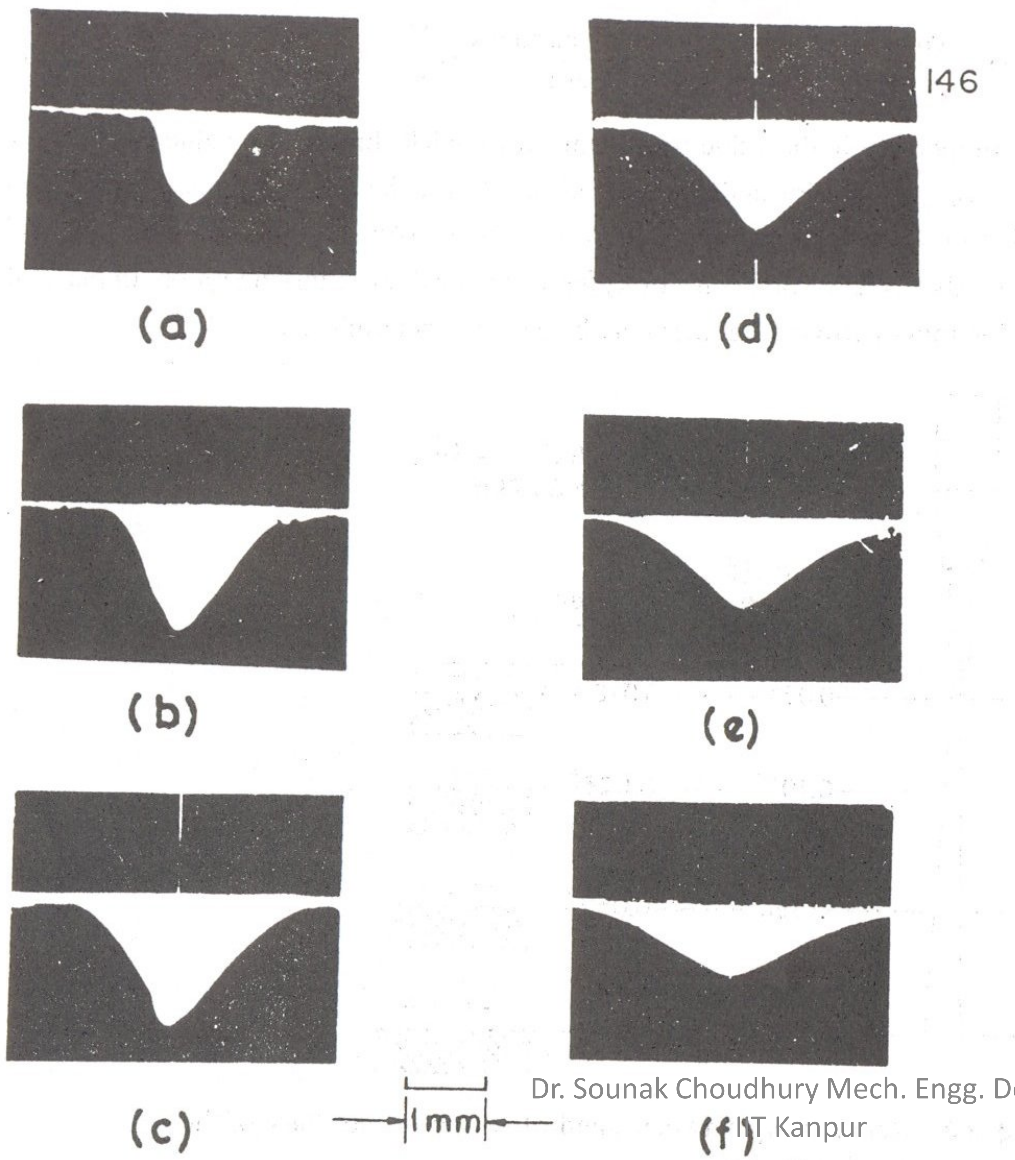
Nozzle to Tip Distance (Stand off distance)

- The nozzle tip distance (NTD) or the stand off distance is a critical parameter in AJM.
- The NTD not only affects the MRR from the work surface but also the shape and size of the cavity produced.
- As shown in the figure below, when the NTD increases, the velocity of the abrasive particles impinging on the work surface increases due to their acceleration after they leave the nozzle. This increases the MRR.
- With a further increase in the NTD, the velocity reduces due to the drag of the atmosphere which initially checks the increase in MRR and then decreases it.





Photographs of the Actual Machined Cavity Profile at Different NTD

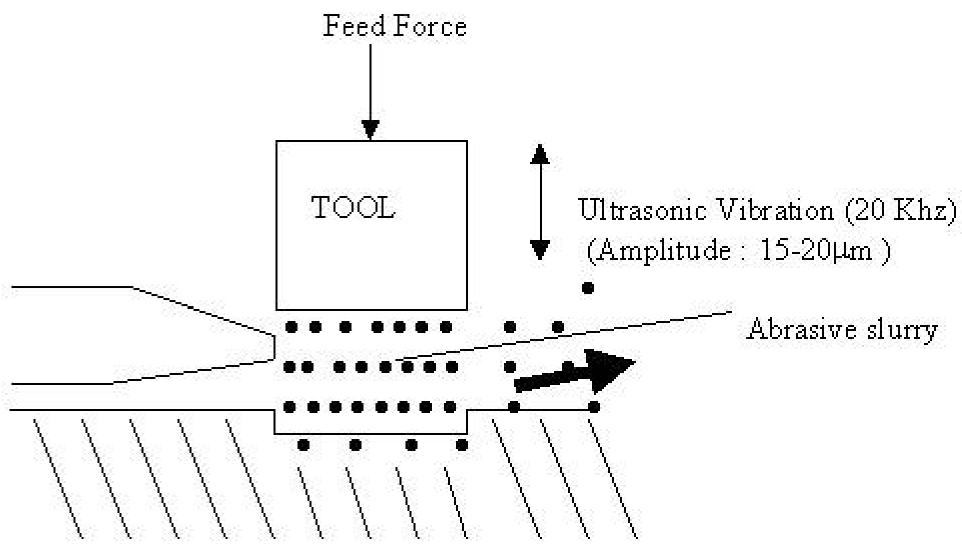


Profile of the machined cavity at different stand off distances

(a) 2mm (b) 6mm
(c) 10mm (d) 14mm
(e) 16mm (f) 20mm

Ultrasonic Machining (USM) Process

- The basic USM process involves a tool (made of a ductile and tough material) vibrating with a low amplitude and very high frequency and a continuous flow of an abrasive slurry in the small gap between the tool and the work piece.
- The tool is gradually fed with a uniform force.
- The impact of the hard abrasive grains fractures the hard and brittle work surface, resulting in the removal of the work material in the form of small wear particles.
- The tool material being tough and ductile wears out at a much slower rate.



Mechanics of USM

The reasons for material removal in an USM process are believed to be:

1. The hammering of the abrasive particles on the work surface by the tool.
2. The impact of free abrasive particles on the work surface.
3. The erosion due to cavitation.
4. The chemical action associated with the fluid used.

USM process

Volume of work material removal rate (Q)

$$Q \propto V Z v$$

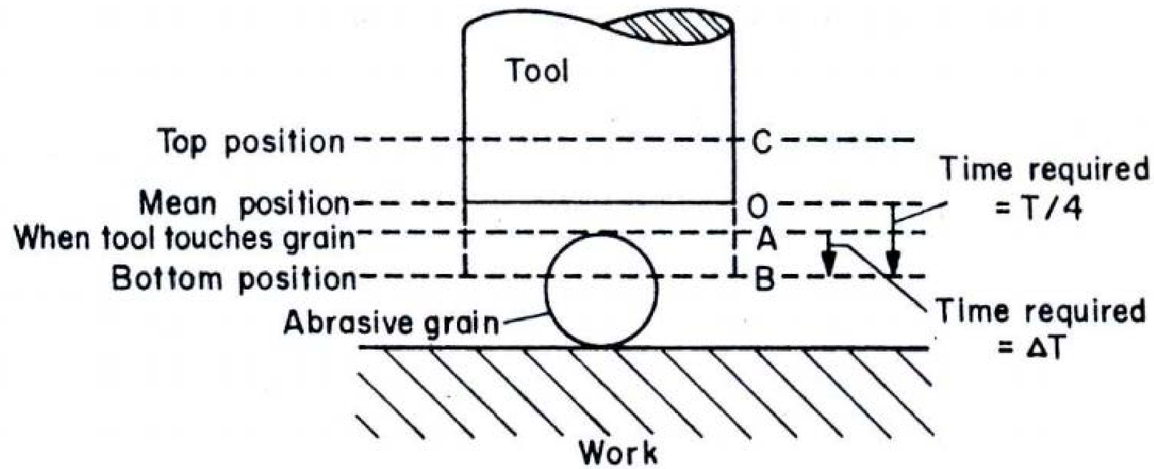
where, V = volume of the work material removal per impact

Z = number of particles making impact per cycle

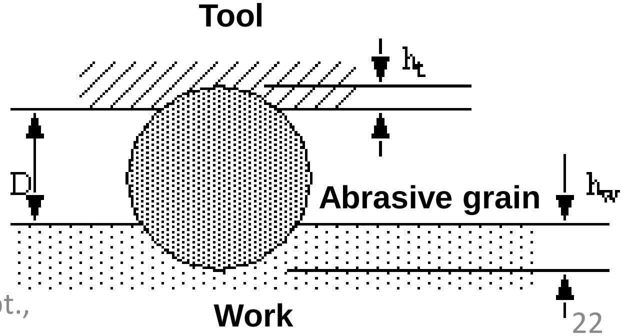
v = frequency

Mechanics of USM

Various Tool Position during a USM cycle.

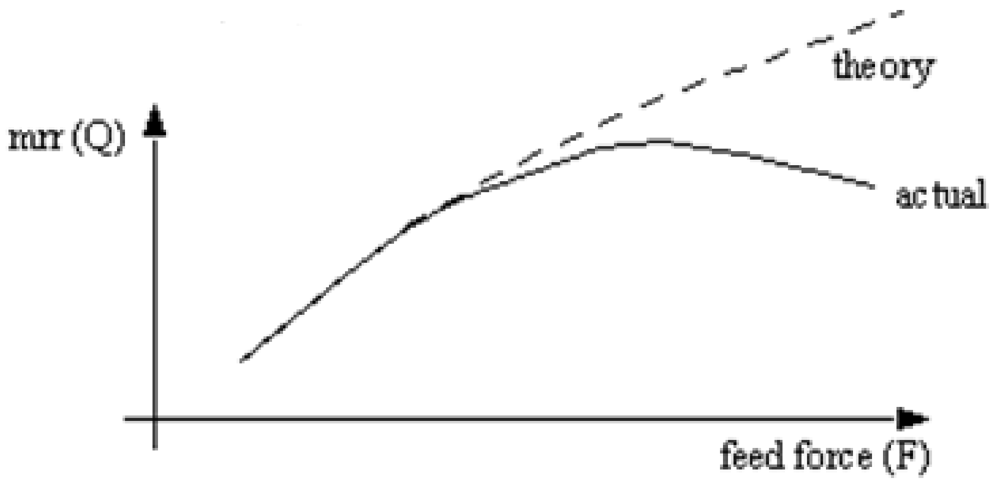


- The position ‘A’ indicates the instant the tool face touches the abrasive grain.
- The period of movement from ‘A’ to ‘B’ represents the impact.
- The indentations, caused by the grain on the tool and the work surface at the extreme bottom position of the tool from the position ‘A’ to position ‘B’ is ‘h’ (the total indentation).



Indentations on tool and work surface at bottom position of the tool

Plot Between MRR and Feed Force



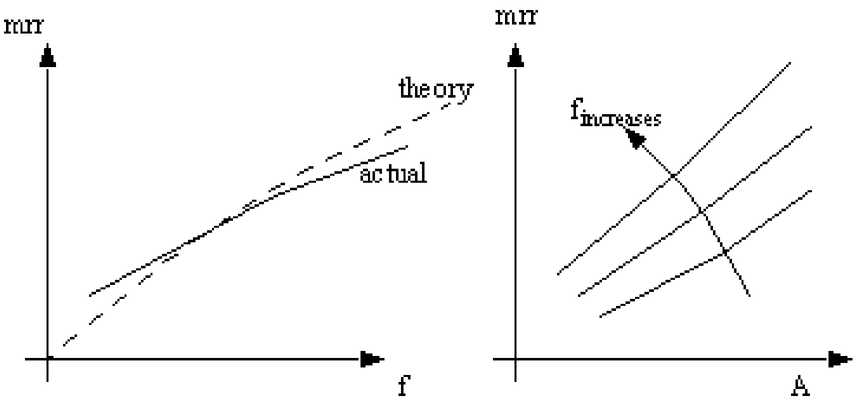
MRR increases with increasing feed force but after a certain critical feed force it decreases because the abrasive grains get crushed under heavy load.

Process Parameters

The important parameters which affect the process are the:

1. Frequency,
2. Amplitude,
3. Static loading (feed force),
4. Hardness ratio of the tool and the workpiece,
5. Grain size,
6. Concentration of the abrasive in the slurry.

(a)

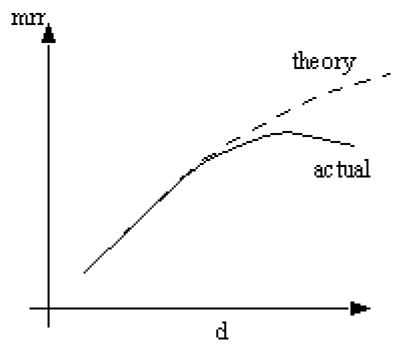


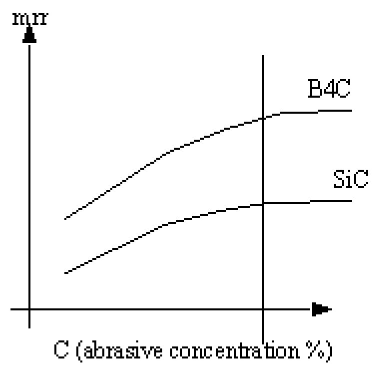
(b)

- With an increase in frequency of the tool head the MRR should increase proportionally. However, there is a slight variation in the MRR with frequency.

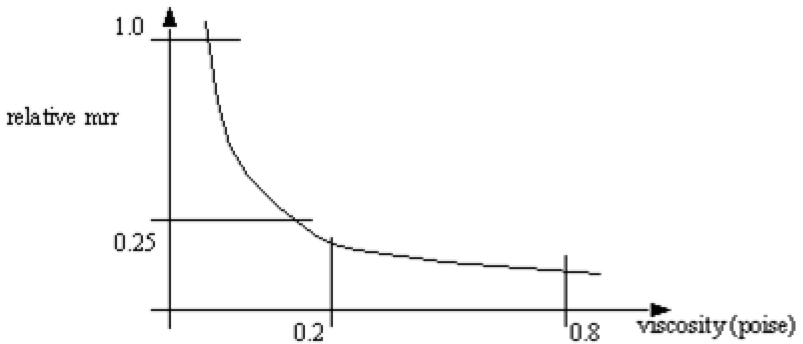
- When the amplitude of the vibration increases the MRR is expected to increase. The actual nature of the variation is shown in Fig. (b). There is some discrepancy in the actual values again. This arises from the fact that we calculate the duration of penetration Δt by considering average velocity.

Process Parameters



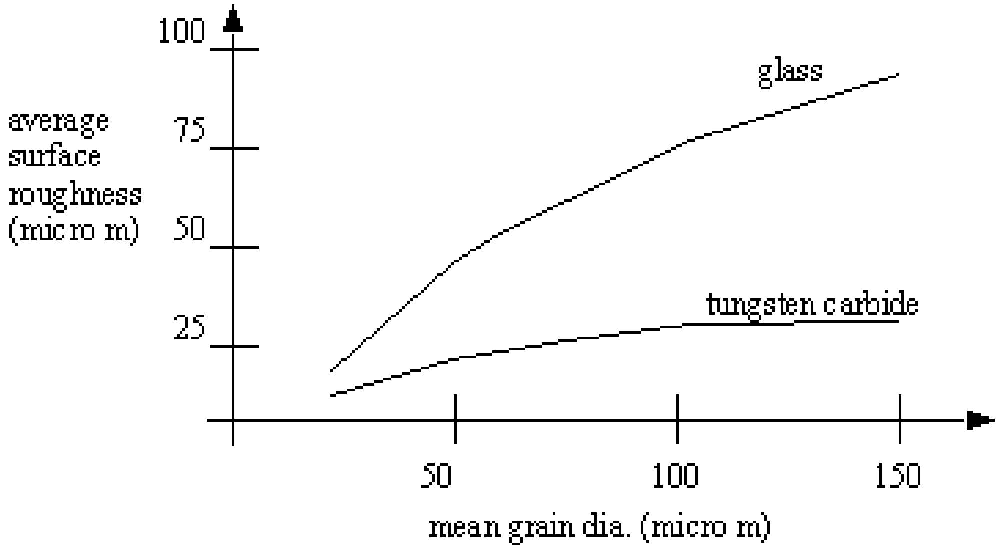


- MRR should also rise proportionately with the mean grain diameter ‘d’. When ‘d’ becomes too large, the crushing tendency increases.
- Concentration of the abrasives directly controls the number of grains producing impact per cycle. MRR is proportional to $C^{1/4}$ so after C rises to 30% MRR increase is not very fast.



- Apart from the process parameters some physical properties (e.g. viscosity) of the fluid used for the slurry also affects the MRR. Experiments show that MRR drops as viscosity increases.
- Although the MRR is a very important consideration for judging the USM but so is the surface finish.

Dependence of Surface Finish on Grain Size

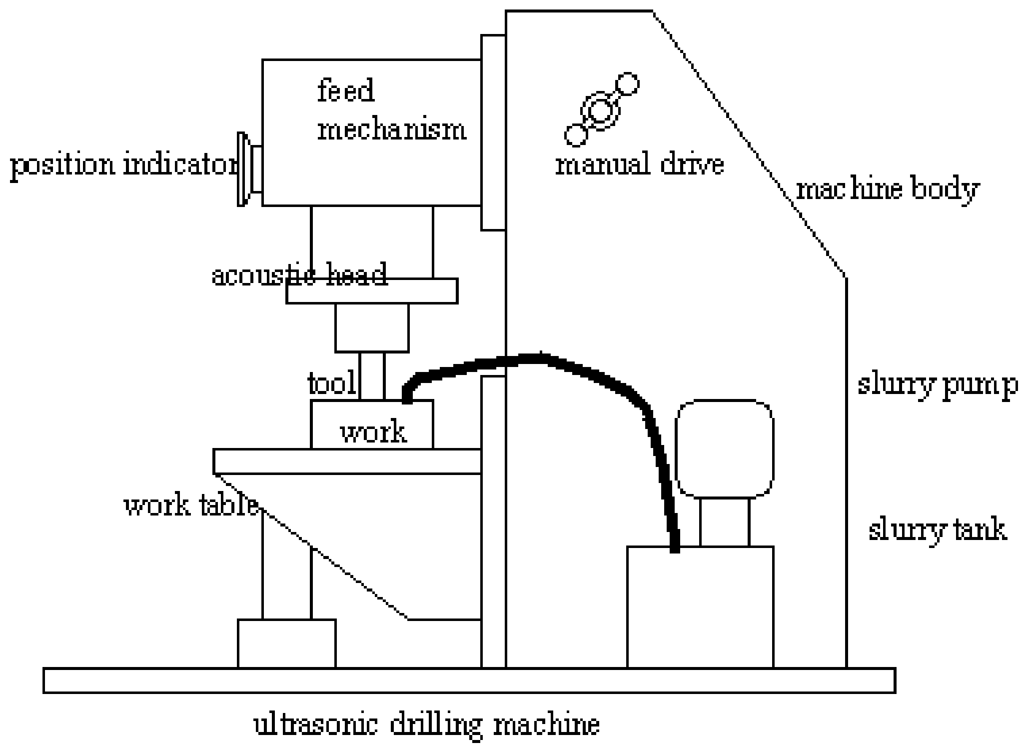


- The figure shows that the surface finish is more sensitive to grain size in case of glass which is softer than tungsten carbide.
- This is because in case of a harder material the size of the fragments dislodged through a brittle fracture does not depend much on the size of the impacting particles.

Ultrasonic Machining Unit

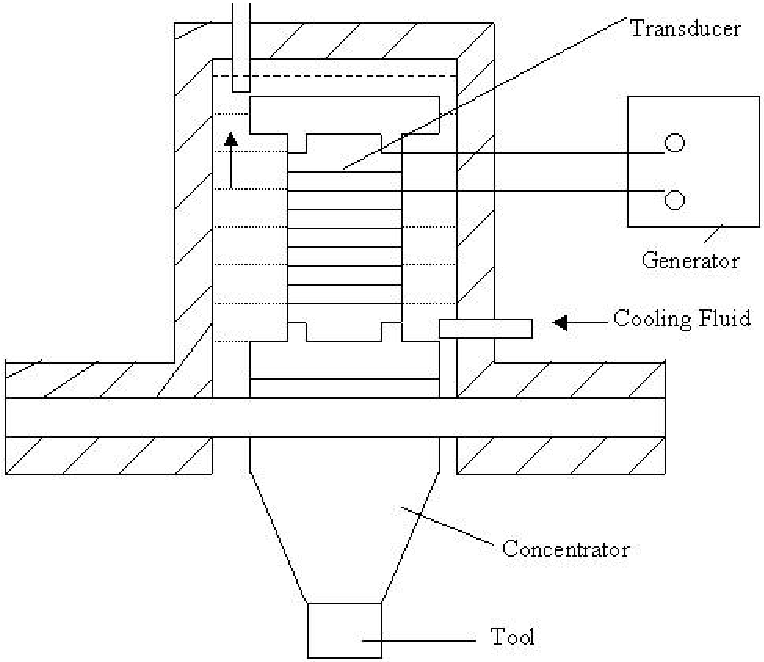
The main units of an Ultrasonic Machining unit are shown in the figure below. It consists of the following machine components:

(1) The acoustic head.
(2) The feeding unit.
(3) The tool.
(4) The abrasive slurry and pump unit.
(5) The body with work table.

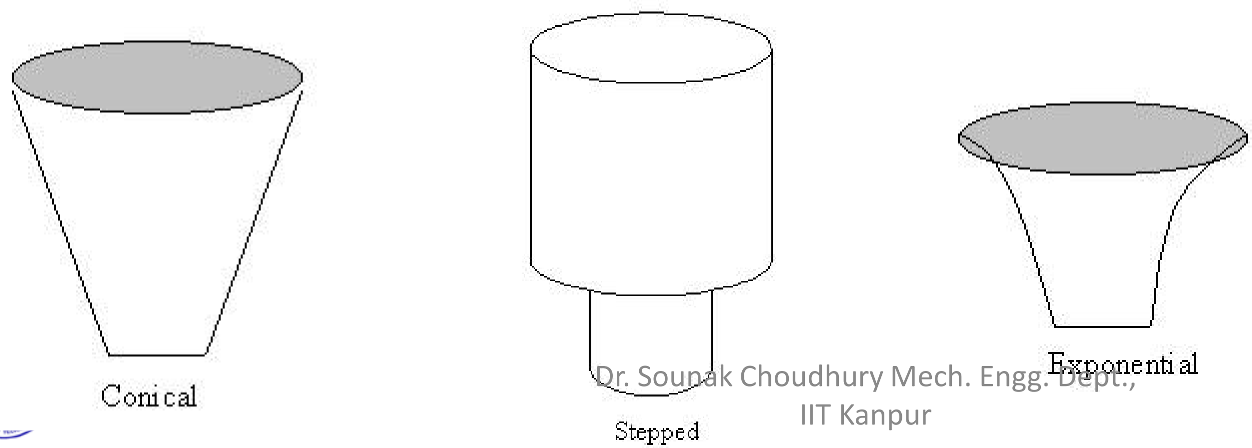


Acoustic Head

1. The Acoustic head's function is to produce a vibration in the tool.
2. It consists of a generator for supplying a high frequency electric current, a transducer to convert this into a mechanical motion (in form of a high frequency vibration).
3. A holder to hold the head.
4. A concentrator to mechanically amplify the vibration while transmitting it to the tool.



Types of concentrators



Abrasive Slurry

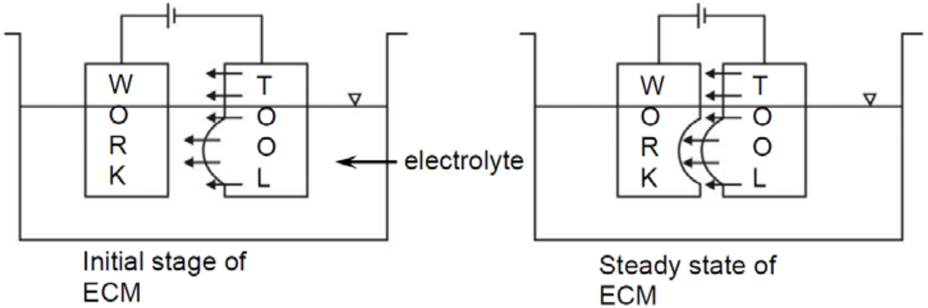
- The most common abrasives are Boron Carbide (B_4C), Silicon Carbide (SiC), Corrundum (Al_2O_3), Diamond and Boron silicarbide.
- B_4C is the best and most efficient among the rest but it is expensive.
- SiC is used on glass, germanium and most ceramics.
- Cutting time with SiC is about 20-40% more than that with B_4C.
- Diamond dust is used only for cutting daimond and rubies.
- Water is the most commonly used fluid although other liquids such as benzene, glycerol and oils are also used.

Summary

Mechanics of material removal	Brittle fracture caused by impact of abreasive grains due to tool vibrating at high frequency
Medium	Slurry
Abrasives	B_4C, SiC, Al_2O_3, diamond 100-800 grit size
Vibration Frequency Amplitude	 15-30 kHz 25-100 μm
Tool Material MRR/Tool wear rate	 Soft steel 1.5 for WC workpiece, 100 for glass workpiece
Gap	25-40 μm
Critical parameters	Frequency, amplitude, tool material, grit size, abrasive material, feed force, slurry concentration, slurry viscosity
Materials application	Metals and alloys (particularly hard and brittle), semiconductors, nonmetals, e.g., glass and ceramics
Shape application	Round and irregular holes, impressions
Limitations	Very low MRR, tool wear, depth of holes and cavities small

Electrochemical Machining (ECM)

- Electrochemical machining is one of the most popular unconventional machining processes.
- The process is actually the reverse of electroplating with some modifications.
- It is based on the principle of electrolysis.
- In a metal, electricity is conducted by free electrons but in a solution the conduction of electricity is achieved through the movement of ions.
- Thus the flow of current through an electrolyte is always accompanied by the movement of matter.
- In the ECM process the work-piece is connected to a positive electrode and the tool to the negative terminal for metal removal.



Schematic principle of Electro Chemical Machining (ECM)

Electro-chemistry of ECM

The reactions at the anode and cathode are:

$$Fe \rightarrow Fe^{++} + 2e \text{ (at anode)}$$

- The electrode metal (Fe) dissolves leaving two electrons

$$2H_2O + 2e \rightarrow H_2\uparrow + 2(OH)^{-} \text{ (at cathode)}$$

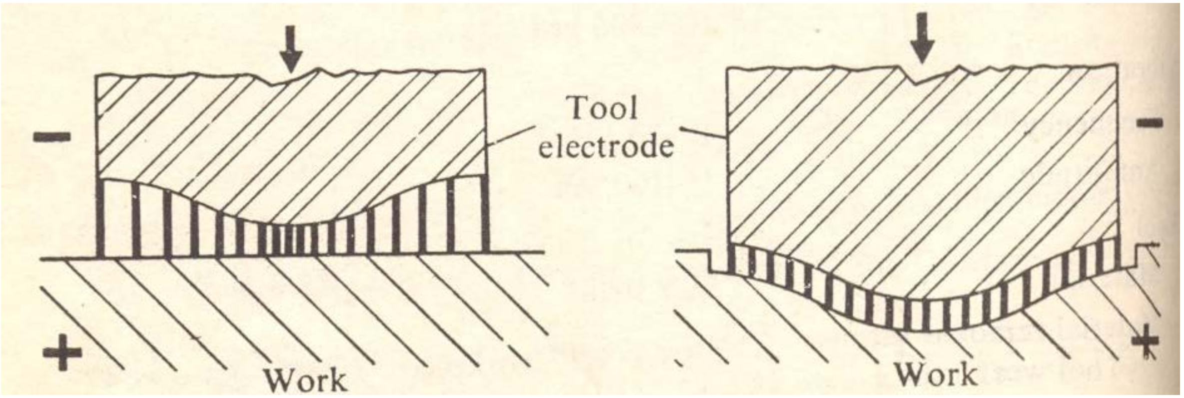
- Positive metal ions tend to move towards the cathode and the negative hydroxyl ions are attracted towards anode.

- The positive metal ions combine with the negatively-charged hydroxyl ions to form Hydroxide:

$$Fe^{++} + 2(OH)^{--} \rightarrow Fe(OH)_2 \downarrow$$

- So, the anode dissolves and H_2 gas is generated at the cathode, leaving the cathode (Tool) shape unchanged.

Electrochemical Machining



- The dissolution rate is more where the gap is less and vice versa.
- This is because the current density is inversely proportional to the gap.
- Now, if the tool is given a downward motion, the work surface tends to take the same shape as that of the tool, and at a steady state the gap is uniform.
- Thus the shape of the tool is represented in the job.

Electrochemical Machining

- In an electrochemical machining process, the electrolyte is pumped at a high pressure through the tool and the small gap between the tool and the work-piece.

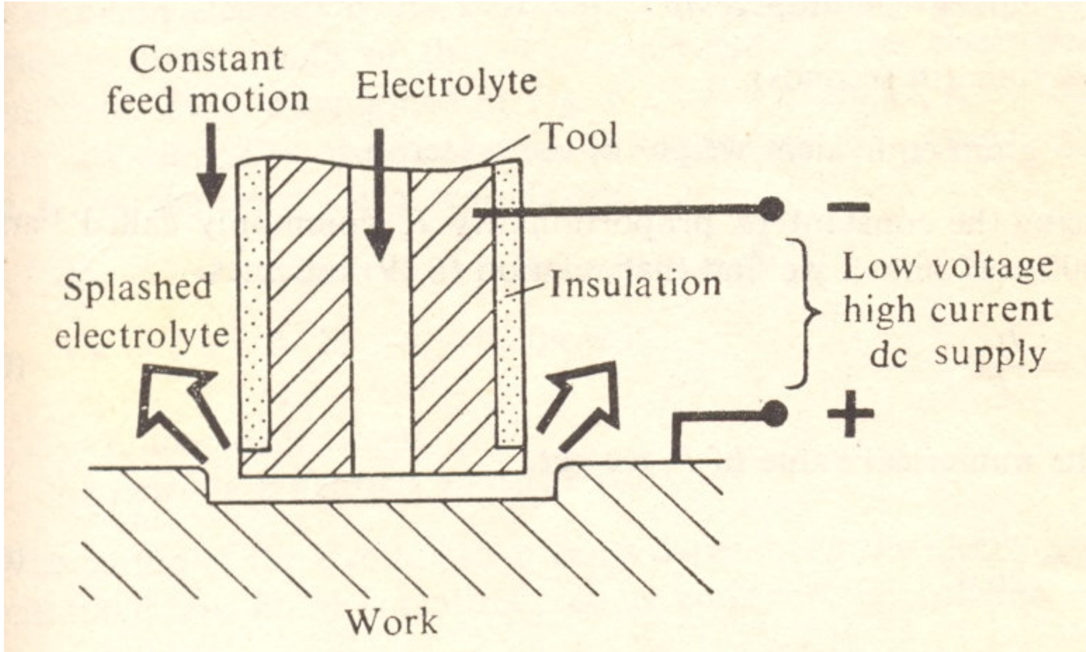
- The electrolyte is so chosen that the anode is dissolved but there is no deposition on the cathode.

- **The order of the current and voltage are a few 1000 amps and 8-20 volts. The gap is of the order of 0.1-0.2 mm .**

- **The metal removal rate is typically 1600 mm^3/sec for each 1000 Amp.**

- **Approximately 3 KW-hr. are needed to remove 16000 mm^3 of metal which is almost 30 times the energy required in a conventional process.**

Electrochemical Machining



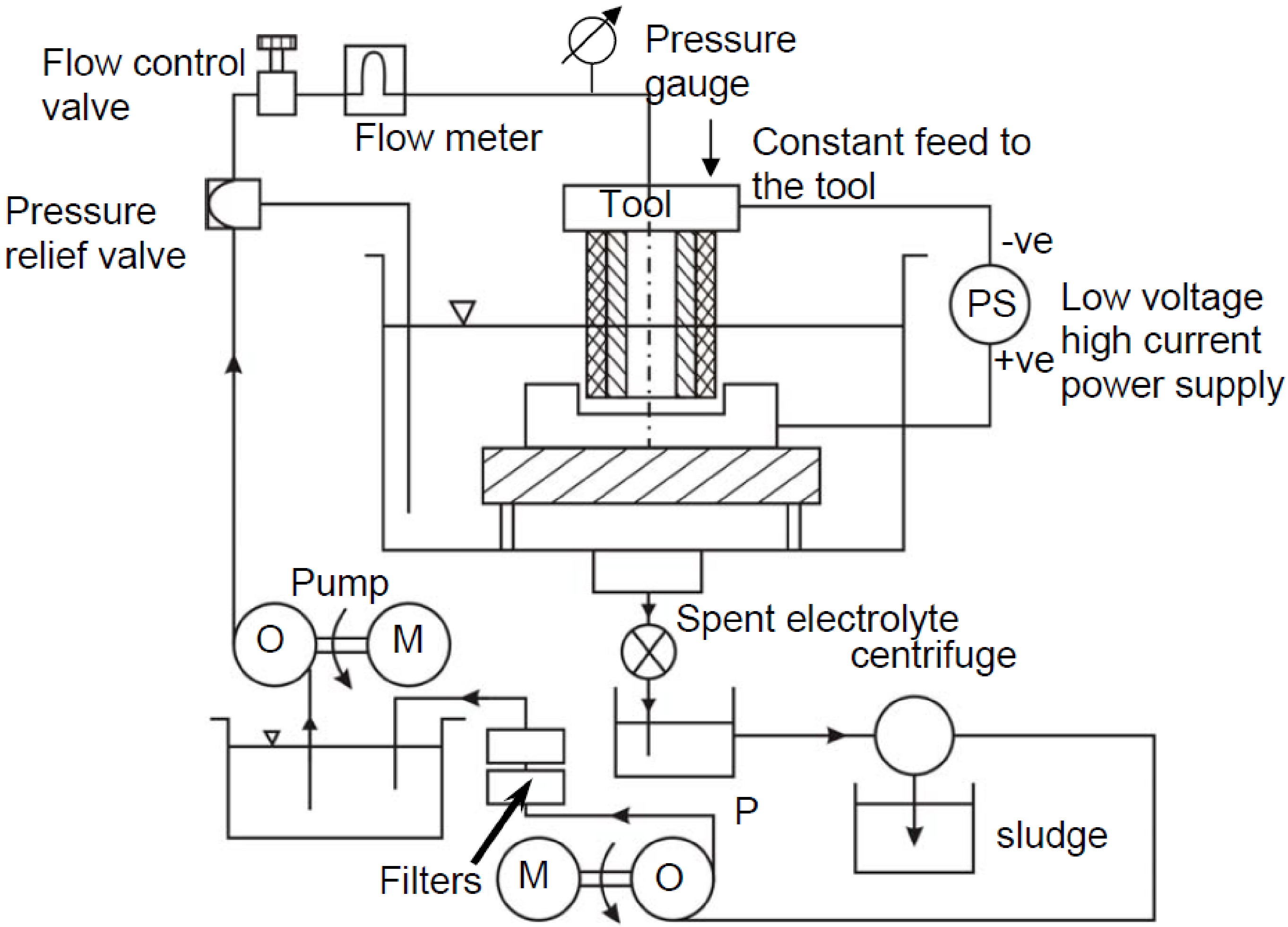
- With ECM the rate of metal removal is independent of the work-piece hardness.

➢ ECM becomes advantageous when either the work material possesses a very low machinability or the shape to be machined is complex.

➢ Unlike most other conventional and unconventional processes, here there is practically no tool wear.

➢ Though it appears that, since machining is done electrochemically, the tool experiences no force, the fact is that the tool and work is subjected to large forces exerted by the high pressure fluid in the gap.

Electro chemical Machining (ECM)



Schematic diagram of an electrochemical drilling unit

Electro chemical Machining (ECM)

Process Parameters

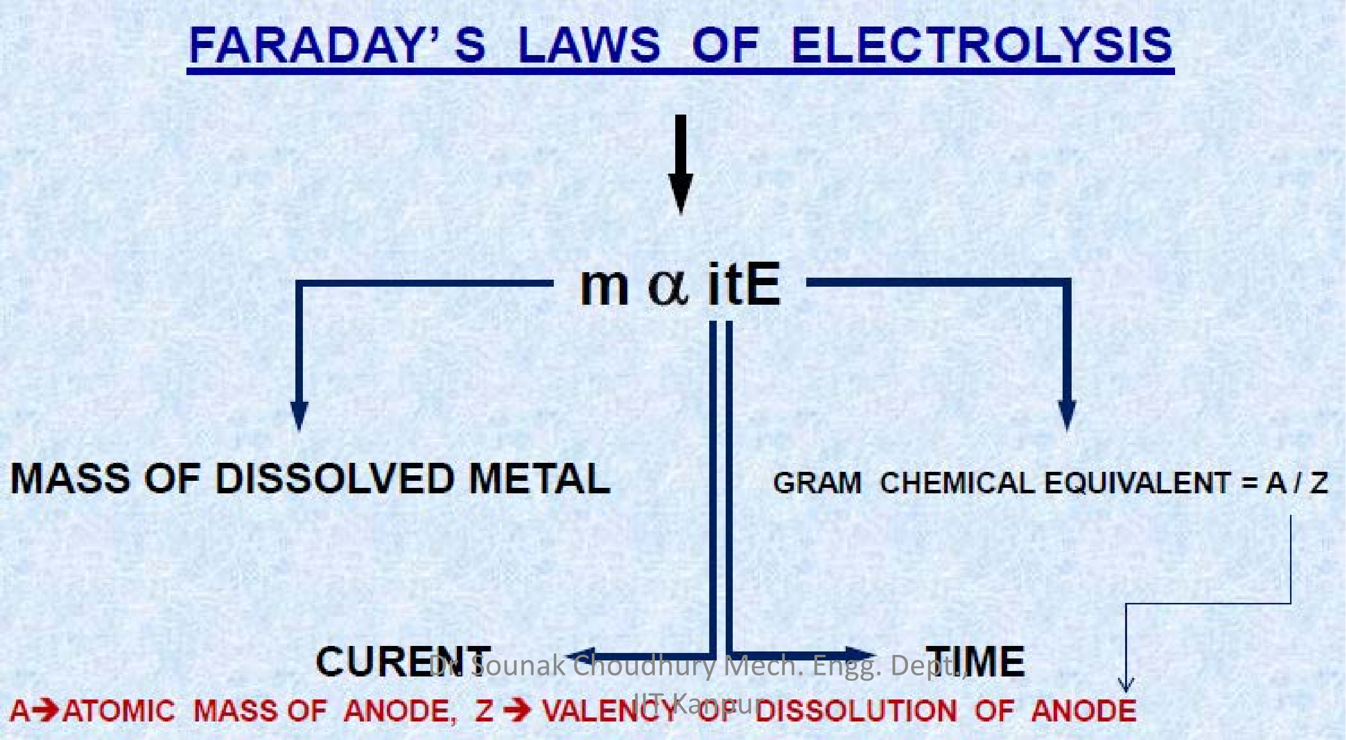
Power Supply		
	Type	direct current
	Voltage	2 to 35 V
	Current	50 to 40,000 A
	Current density	0.1 A/mm^2 to 5 A/mm^2
Electrolyte		
	Material	NaCl and $NaNO_3$
	Temperature	20^{o}C – 50^{o}C
	Flow rate	20 lpm per 100 A current
	Pressure	0.5 to 20 bar
	Dilution	100 g/l to 500 g/l
Working gap		0.1 mm 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

Electrochemistry of ECM process

The electrolysis process is governed by the following two laws proposed by Faraday.

(1) The amount of chemical change produced by an electric current, that is, the amount of any material dissolved or deposited, is proportional to the quantity of electricity passed.

(2) The amounts of different substances dissolved or deposited by the same quantity of electricity are proportional to their chemical equivalent weights.



Material Removal in ECM Process

MATERIAL REMOVAL (m) IN ECM *FOLLOWS FARADAY'S LAWS*

OF ELECTROLYSIS:

$$m = \frac{ItE}{F} \qquad \text{.......(1)}$$

MATERIAL RAMOVAL RATE (MRR) CAN BE OBTAINED AS

$$\frac{m}{t} = \dot{m} = \frac{IE}{F} \qquad \text{.......(1a)}$$

Where, 'm' is amount of material removed in grams, 'I' is current flowing through the IEG in Amperes, 't' Is time of current flow (or ECM), 'E' Is gram chemical equivalent of anode material, 'F' is Faraday's constant (Coulombs or A.s) or constant of proportionality. and $\dot{m}$ is material removal rate in g/s.

Material Removal in ECM Process

MRR CAN BE OBTAINED AS

$$\frac{\rho_a v_a}{t} = \frac{\rho_a A_a (y_a)}{(t)} = \frac{IE}{F}$$

WHERE, ρ_a = DENSITY OF ANODE, V_a = VOLUME OF MATERIAL REMOVED FROM THE ANODE IN TIME 't', A_a = X- SECTIONAL AREA ON THE ANODE FROM WHICH MATERIAL IS BEING REMOVED IN TIME 't', y_a IS THE THICKNNESS OF MATERIAL REMOVED IN TIME 't'. ΔV IS OVER POTENTIAL, k= ELECTROLYTE'S ELECTRICAL CONDUCTIVITY

Material Removal in ECM Process

FROM ABOVE EQUATION, WE CAN WRITE

$$\therefore MRR_l = \frac{(y_a)}{(t)} = \frac{IE}{F\rho_a A_a}$$

$$\boxed{MRR_l = \frac{JE}{F\rho_a}} \quad \text{.......(2)}$$

(J = CURRENT DENSITY = I/Aa)

ABOVE EQUATION CAN BE WRITTEN AS

$$MRR_l = \left(\frac{V-\Delta V}{A_a}\right)\left\{\frac{kA_a}{y}\right\}\frac{E}{F\rho_a}$$

J=I/Aa=V/R=V/(ρl/A)

ρ =(1/k)

J=((V- ΔV)/A) (kA/y)

ρ=Resistance

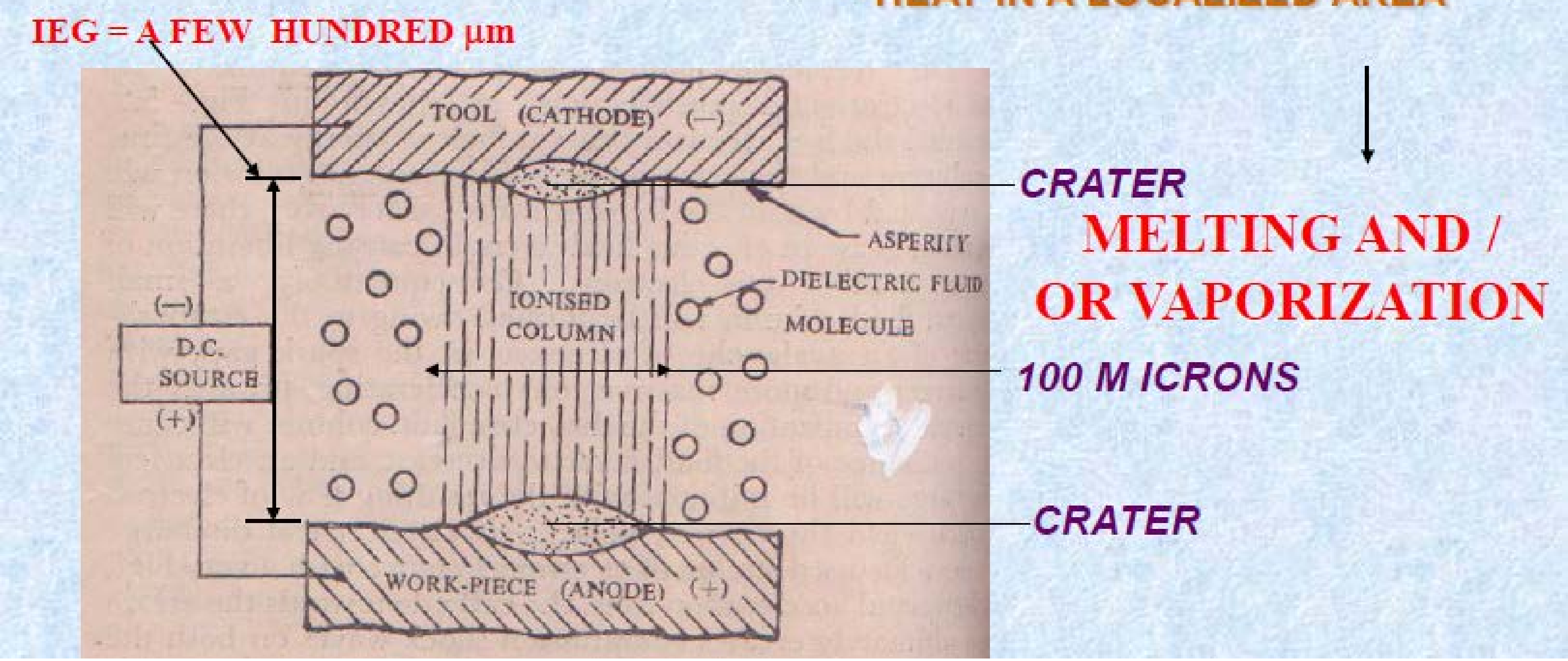
Anode density

ELECTRIC DISCHARGE MACHINING (EDM)

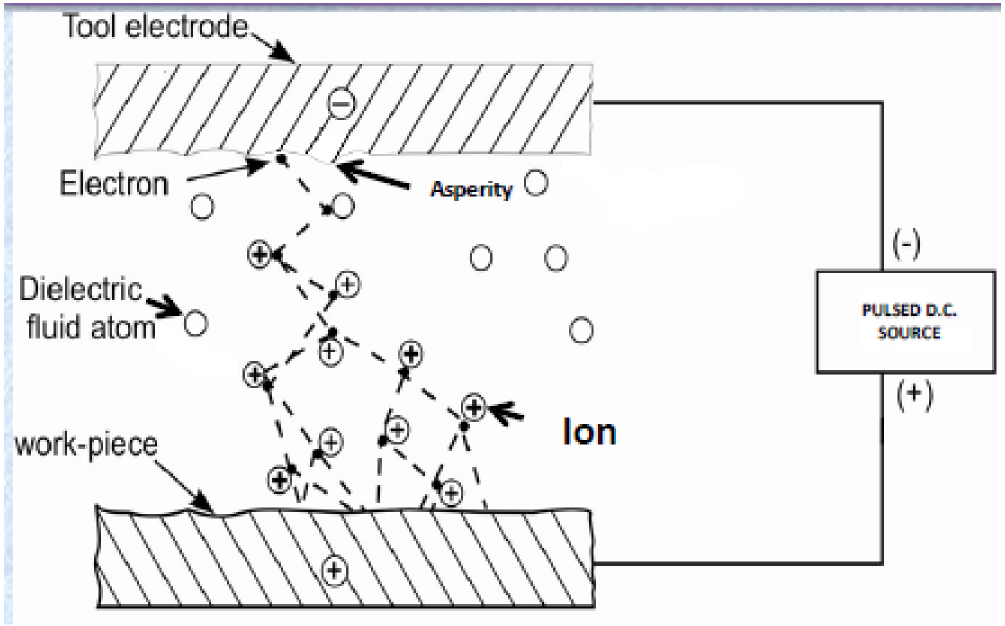
Electric Discharge Machining (EDM)

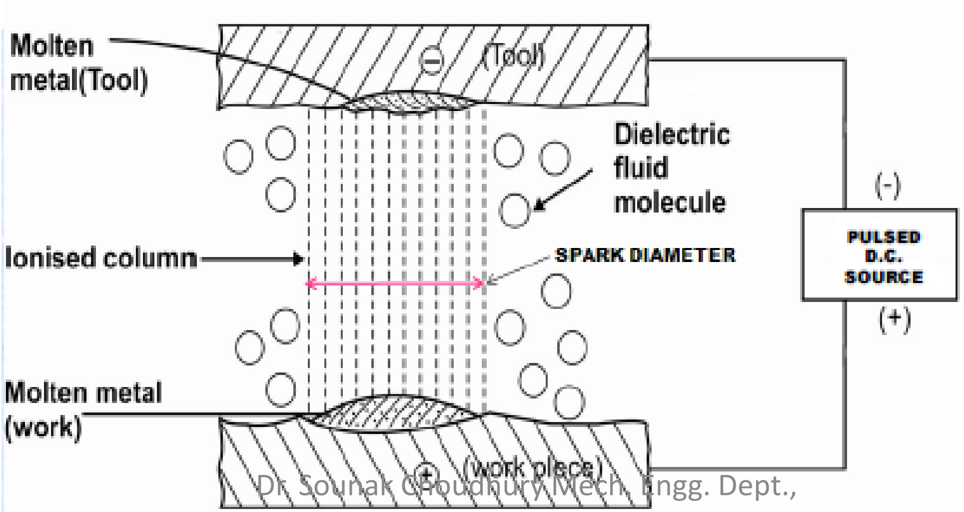
•*SPARKS* CREATED DELIBERATELY

• HEAT IN A LOCALIZED AREA



EDM: How Sparking Takes Place?

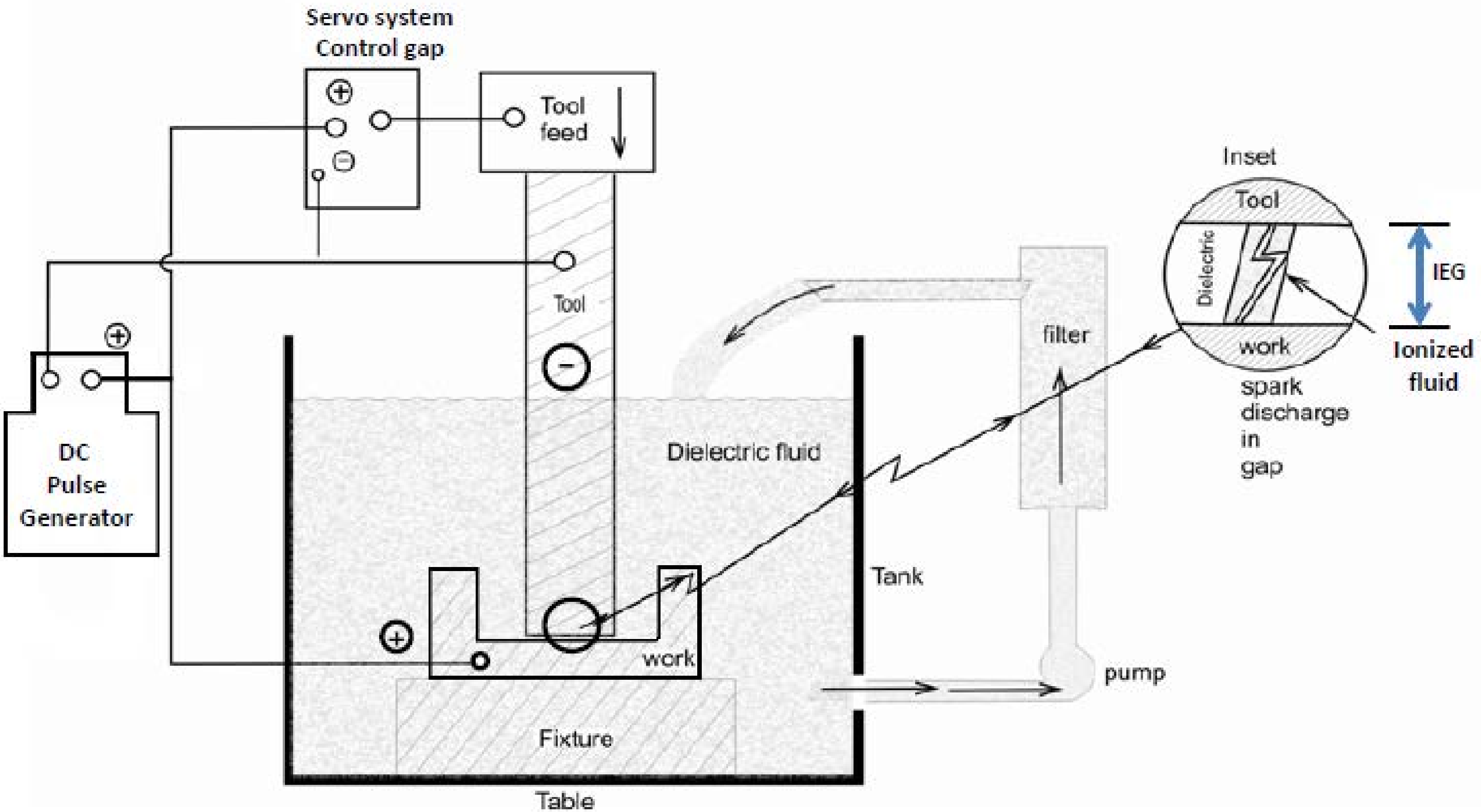




Mechanics of EDM

- Local gap between anode (Work) and Cathode (Tool) varies due to asperities
- Electrostatic field is created at the minimum gap due to voltage
- It causes cold emission of electrons from the cathode
- Liberated electrons accelerate towards the anode
- Electrons collide with the molecules of dielectric fluid, breaking them into electrons and positive ions
- Produced electrons dislodge more electrons from the dielectric molecules
- A narrow column of ionised dielectric fluid molecules is established in the gap connecting two electrodes
- Causing an avalanche of electrons, seen as a spark
- Spark results in a compression shock wave and develops a very high temperature of 10,000 – 12,000^{0}C
- Causes work material to melt and evaporate

EDM: Machine Elements

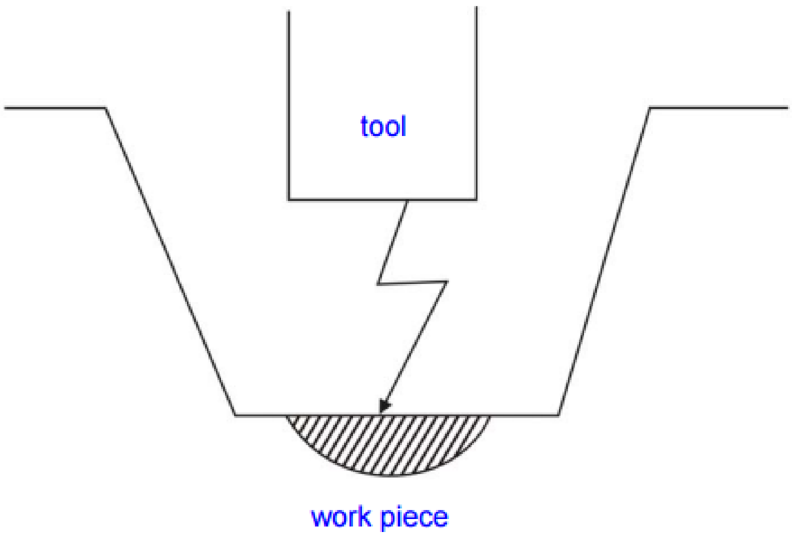


REPLICA OF THE TOOL → WORKPIECE

MRR in EDM

The molten crater can be assumed to be hemispherical in nature with a radius r which forms due to a single pulse or spark. Hence, material removal in a single spark can be expressed as

$$\Gamma_s = \frac{2}{3}\pi r^3$$



The energy content of a single spark is given as

$$E_s = VIt_{on}$$

Thus the energy available as heat at the workpiece is given by $E_w \ \alpha \ E_s$

$$E_w = kE_s$$

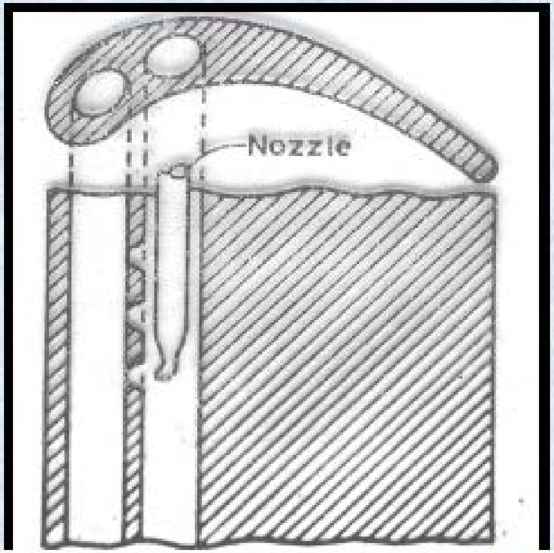
Now, it can be logically assumed that material removal in a single spark would be proportional to the spark energy. $\Gamma_s \ \alpha \ E_s \ \alpha \ E_w$

$$\therefore \quad \Gamma_s = gE_s$$

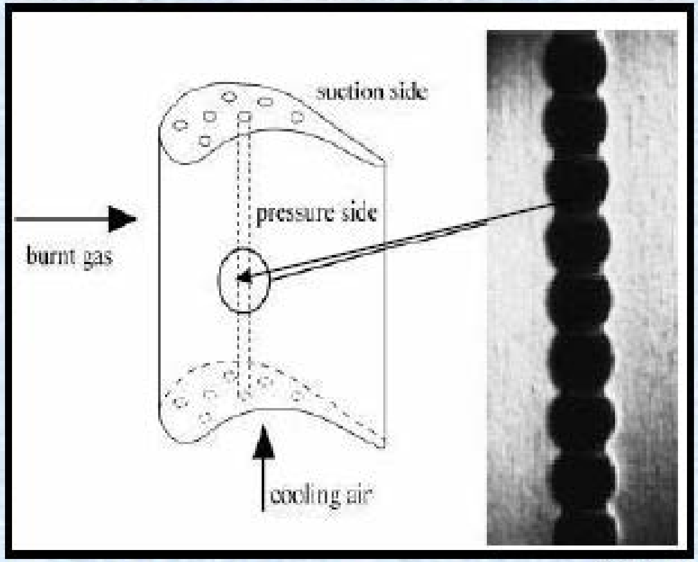
Now, material removal rate is the ratio of material removed in a single spark to cycle time. Thus,

$$MRR = \frac{\Gamma_s}{t_c} = \frac{\Gamma_s}{t_{on} + t_{off}} \Rightarrow MRR = g\frac{VIt_{on}}{t_{on} + t_{off}} = g\frac{VI}{\left(1 + \frac{t_{off}}{t_{on}}\right)}$$

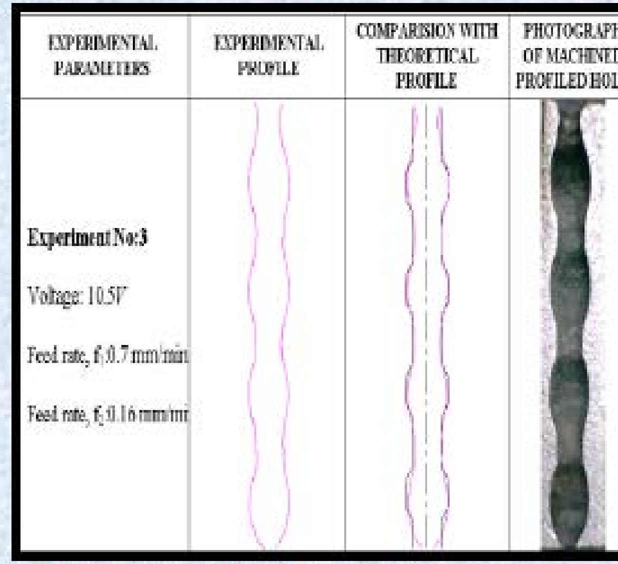
ELECTROCHEMICAL MACHINING



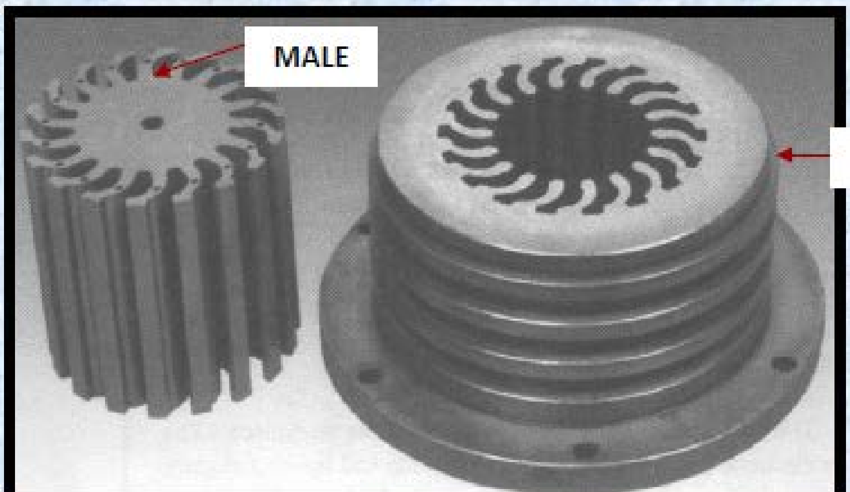
HOLE NORMAL TO THE WALL



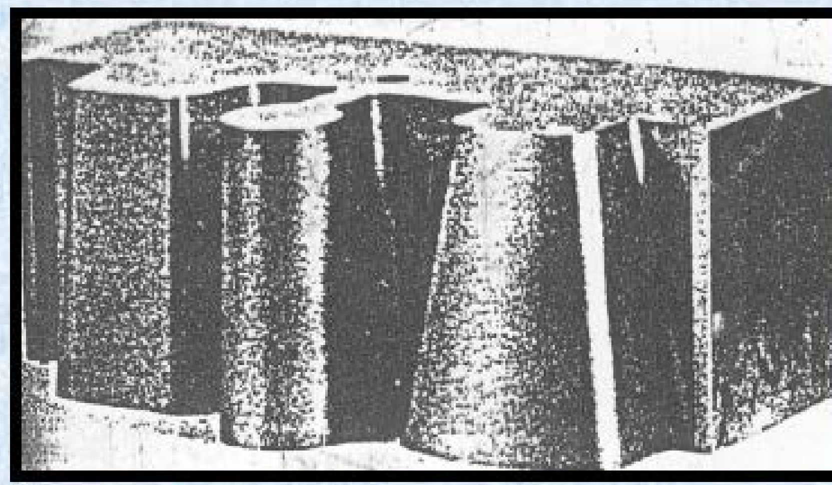
Turbine Blade with cooling Holes



Contoured Hole Drilled In Inconel Using ECM



Precision wire EDM



Taper 3D cutting using traveling wire EDM

Advantages of EDM

- Any materials that are electrically conductive can be machined by EDM.
- Materials, regardless of their hardness, strength, toughness and microstructure can be easily machined/cut by EDM process.
- The tool (electrode) and workpiece are free from cutting forces.
- Edge machining and sharp corners are possible in EDM process.
- The tool making is easier as it can be made from softer and easily formable materials like copper, brass and graphite.

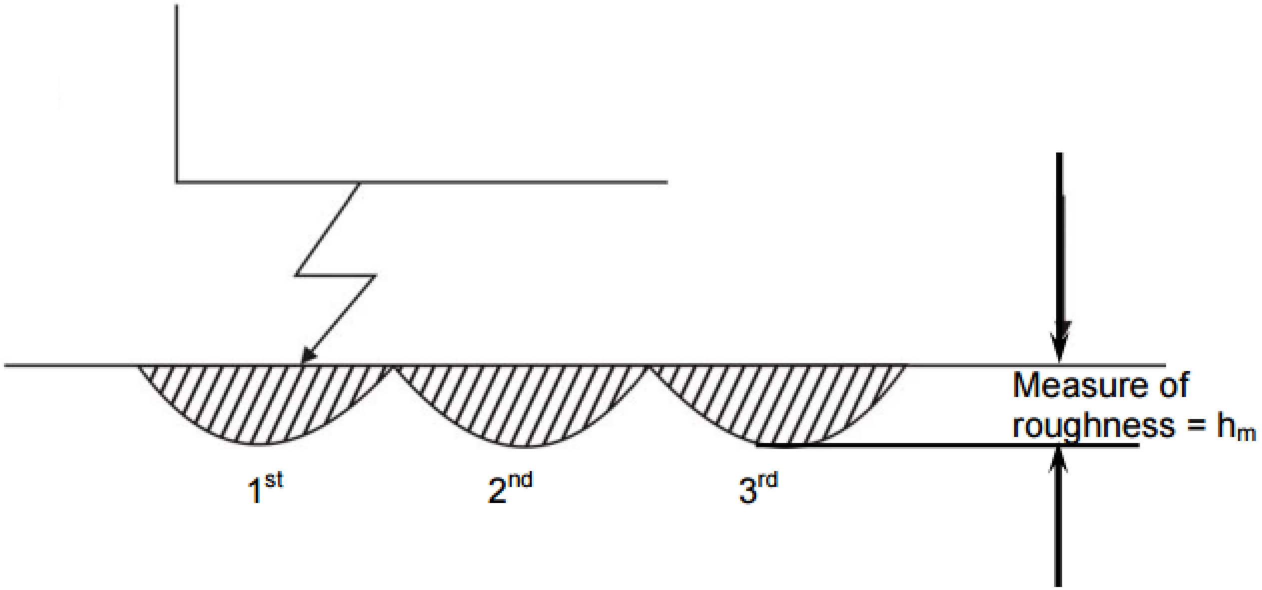
Advantages of EDM

- The process produces good surface finish, accuracy and repeatability.
- Hardened workpieces can also be machined since the deformation caused by it does not affect the final dimensions.
- EDM is a burr free process.
- Hard die materials with complicated shapes can be easily finished with good surface finish and accuracy through EDM process.
- Due to the presence of dielectric fluid, there is very little heating of the bulk material.

Limitations of EDM

- Material removal rates are low, making the process economical only for very hard and difficult to machine materials.
- Re-cast layers and micro-cracks are inherent features of the EDM process, thereby making the surface quality poor.
- The EDM process is not suitable for non-conductors.
- Rapid electrode wear makes the process more costly.
- The surfaces produced by EDM generally have a matt type appearance, requiring further polishing to attain a glossy finish.

Surface Finish in EDM



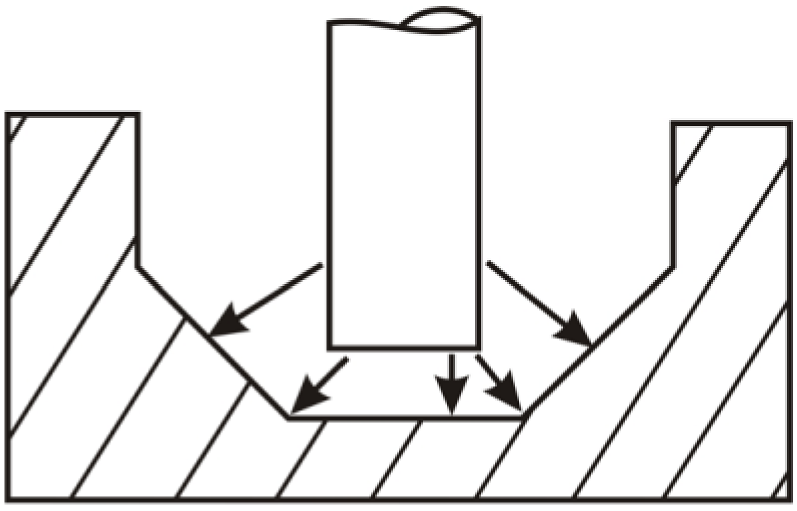
$$h_m = r \quad \text{and} \quad \Gamma_s = \frac{2}{3}\pi r^3$$

$$\therefore \quad r = h_m = \left(\frac{3}{2}\Gamma_s\right)^{1/3}$$

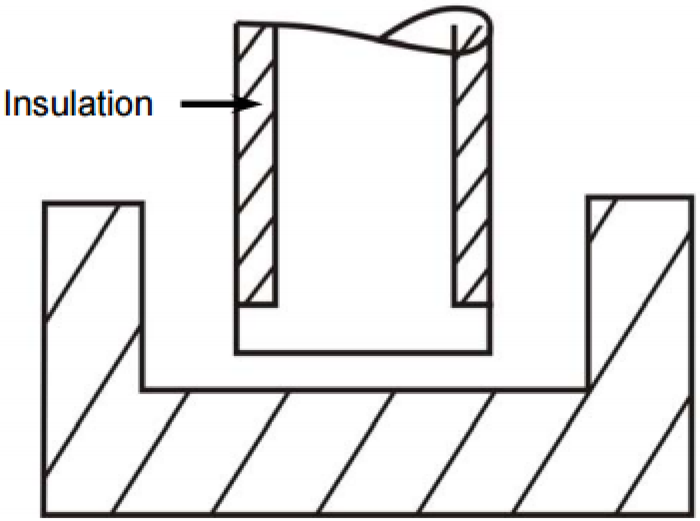
$$\text{Now} \quad \Gamma_s = gE_s = gVIt_{on}$$

$$\therefore \quad h_m \;\alpha\; (\Gamma_s)^{1/3} \;\alpha\; \{VIt_{on}\}^{1/3}$$

Tapercut and Overcut in EDM



tapercut and overcut



tapercut prevention

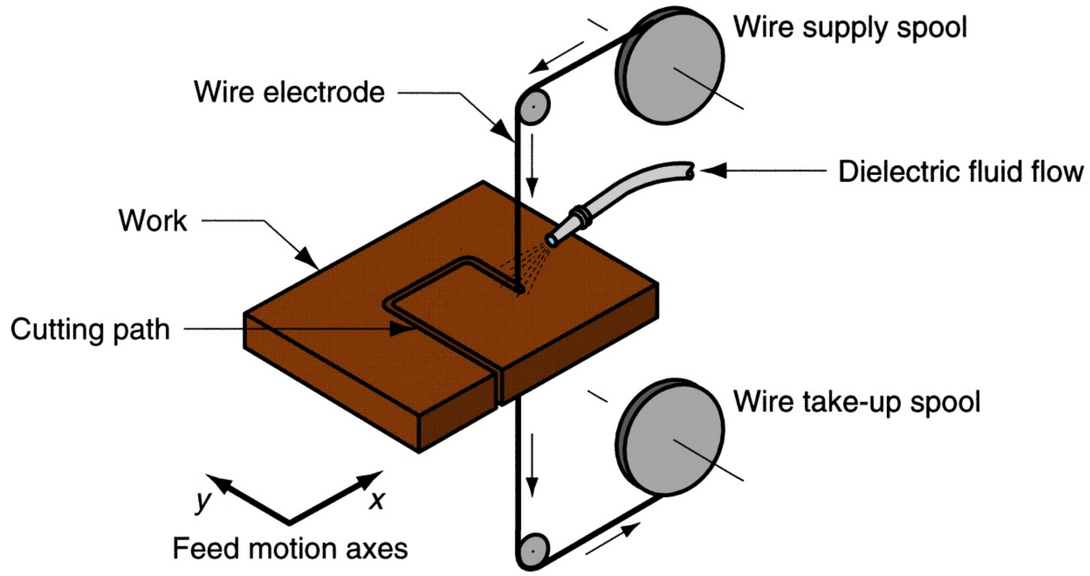
Applications of EDM

- Hardened steel dies, stamping tools, wire drawing and extrusion dies, header dies, forging dies, intricate mould cavities and such parts are made by the EDM process.
- The process is widely used for machining of exotic materials that are used in aerospace and automotive industries.
- EDM being a non-contact type of machining process, it is very well suited for making fragile parts that cannot take the stress of machining.

  Ex: washing machine agitators, electronic components, printer parts and difficult to machine features such as the honeycomb shapes.
- Deep cavities, slots and ribs can be easily made by EDM.
- Micro-EDM process can successfully produce micro-pins, micro-nozzles and micro-cavities.

Wire EDM

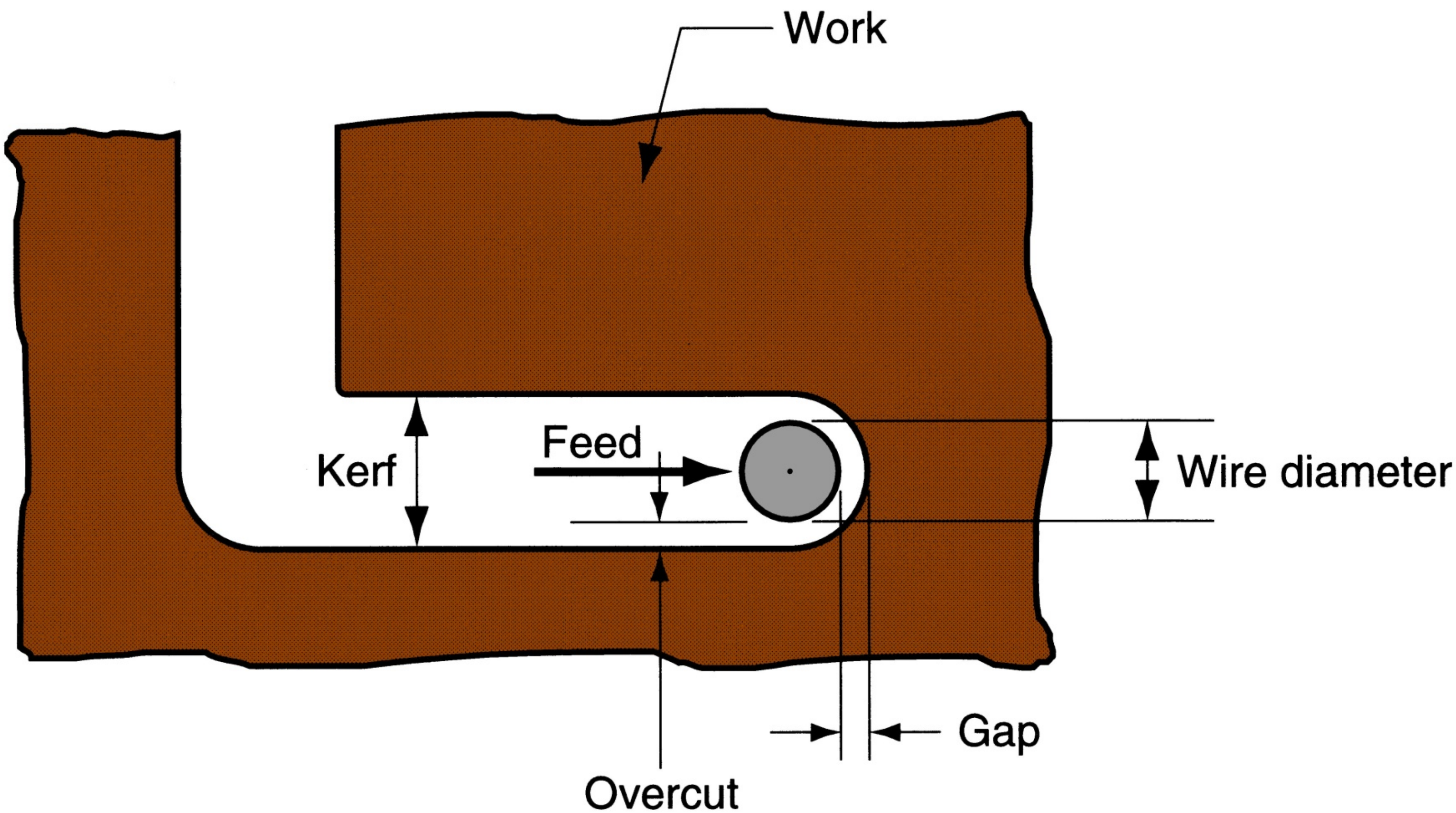
Special form of EDM that uses small diameter wire as electrode to cut a narrow kerf in work



Electric discharge wire cutting (EDWC), also called wire EDM

Operation of Wire EDM

- Work is fed slowly past wire along desired cutting path, like a bandsaw operation
- CNC used for motion control
- While cutting, wire is continuously advanced between supply spool and take-up spool to maintain a constant diameter
- Dielectric required, using nozzles directed at tool-work interface or submerging workpart



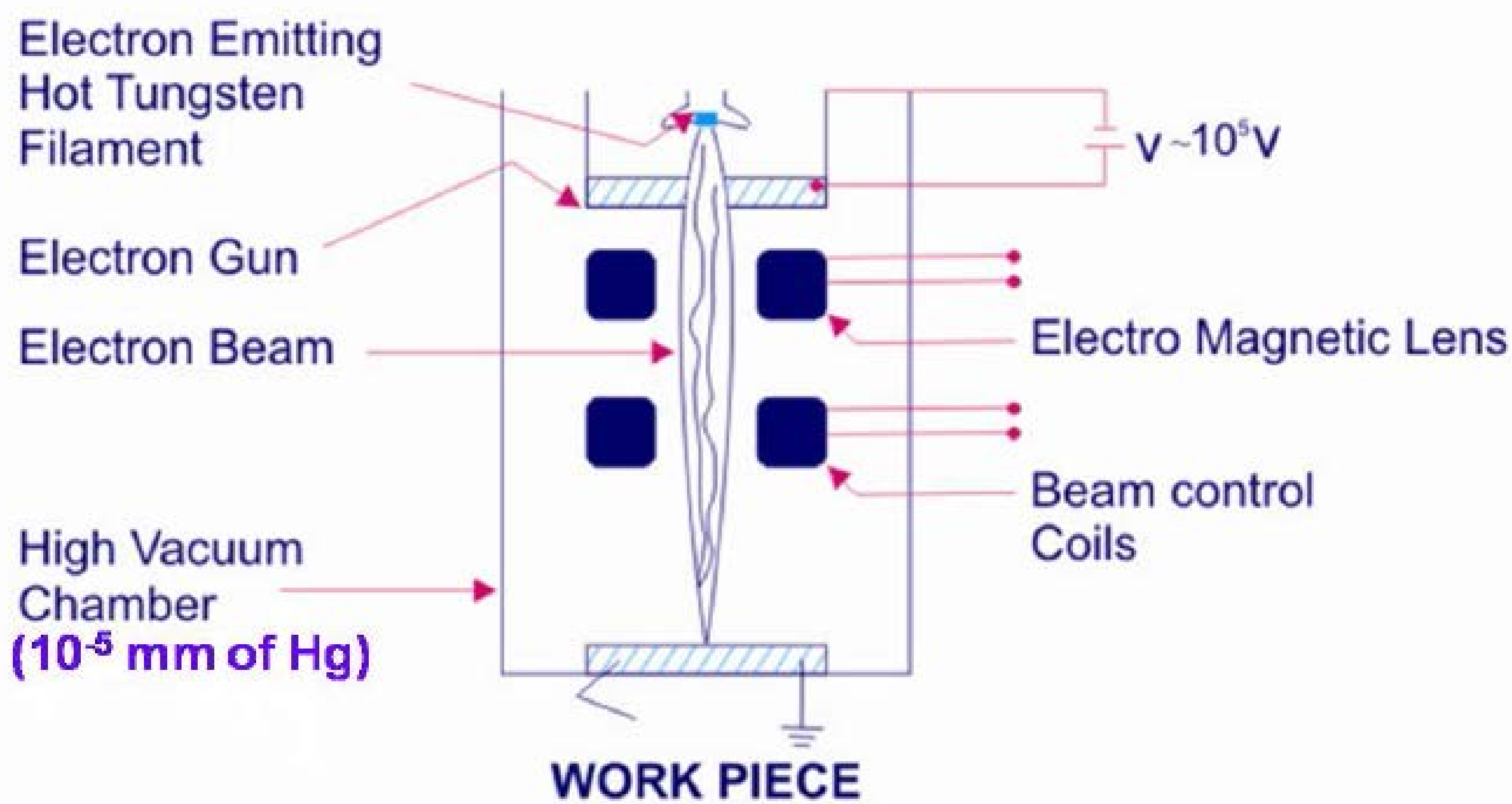
Definition of kerf and overcut in electric discharge wire cutting

Wire EDM Applications

- Ideal for stamping die components
  - Since kerf is so narrow, it is often possible to fabricate punch and die in a single cut

- Other tools and parts with intricate outline shapes, such as lathe form tools, extrusion dies, and flat templates

ELECTRON BEAM MACHINING (EBM)



EBM

EBM Operation

- EB gun accelerates a continuous stream of electrons to about 75% of light speed
- Beam is focused through electromagnetic lens, reducing diameter to as small as 0.025 mm (0.001 in)
- On impinging work surface, kinetic energy of electrons is converted to thermal energy of extremely high density which melts or vaporizes material in a very localized area

EBM Applications

- Works on any known material
- Ideal for micromachining
  - Drilling small diameter holes - down to 0.05 mm (0.002 in)
  - Cutting slots only about 0.025 mm (0.001 in.) wide
- Drilling holes with very high depth-to-diameter ratios
  - Ratios greater than 100:1