NON TRADITIONAL MACHINING

Unit I : Introduction to Non-traditional machining processes : Classifications of material removal processes, Need for non-conventional or non-traditional processes, Characteristics of non-traditional material removal (machining) processes, Chemical and Photo-chemical machining, Electrochemical machining, Electrochemical grinding

Unit II : Nontraditional machining processes (Mechanical) : Ultrasonic machining, Abrasive jet machining, Water jet machining, Abrasive water jet machining

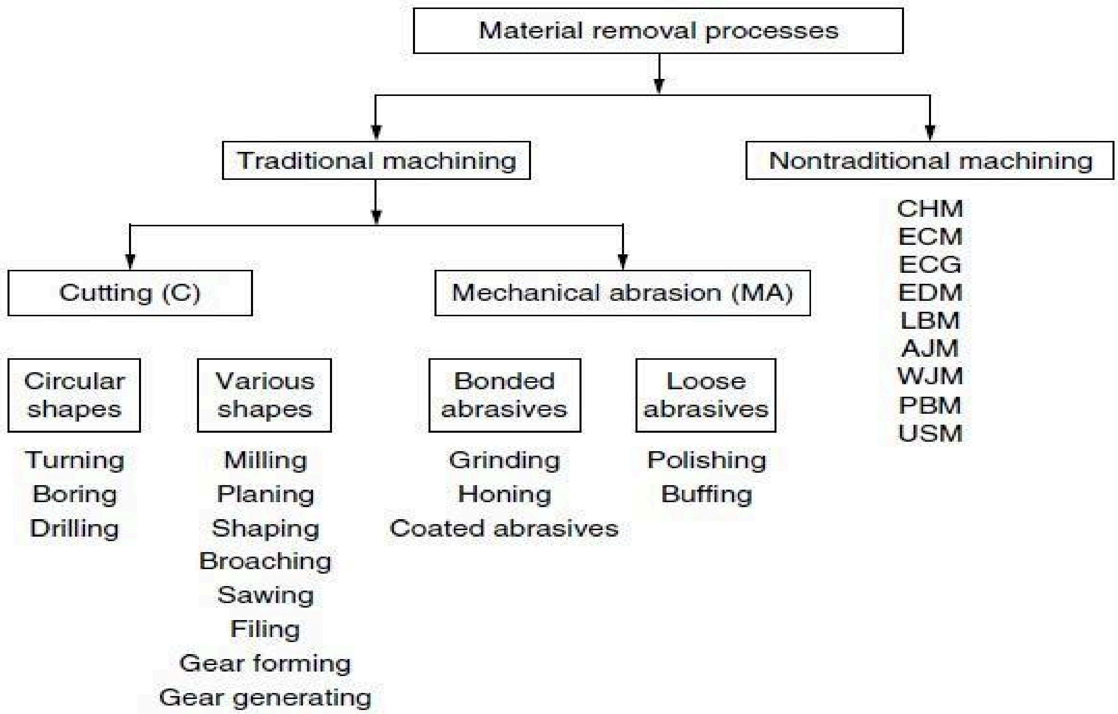
Unit III : Nontraditional machining processes (Thermal) : Electric discharge machining, Laser beam machining, Electron beam machining-thermal and non-thermal, Plasma machining, Thermal spraying processes-combustion (Detonation gun process) and electrical (plasma spraying), Rapid prototyping

Content

Unit I : Introduction to Non-Traditional Machining Processes :

Classifications of Material Removal

- Non-traditional manufacturing processes are defined as a group of processes that remove excess material by various techniques involving **mechanical, thermal, electrical or chemical energy** or combinations of these energies but do not use a sharp cutting tool as it needs to be used for traditional manufacturing processes.
- Extremely hard and brittle materials are difficult to machine by traditional machining processes such as turning, drilling, shaping and milling.
- Employed where traditional machining processes are not feasible



Need for Non-Conventional or Non-Traditional Processes

Use of non-traditional machining

- 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.

Characteristics of Non-Traditional Material Removal (Machining) Processes

- Process performance is independent of workpiece : Strength & Hardness are not a barrier.
- Performance depends on thermal, electrical and chemical properties of workpiece materials.
- Uses different kinds of energy in direct form.
- In general, low MRR but better-quality products.
- Comparatively high initial investment cost of machine tools and high operating cost.

Classifications 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.

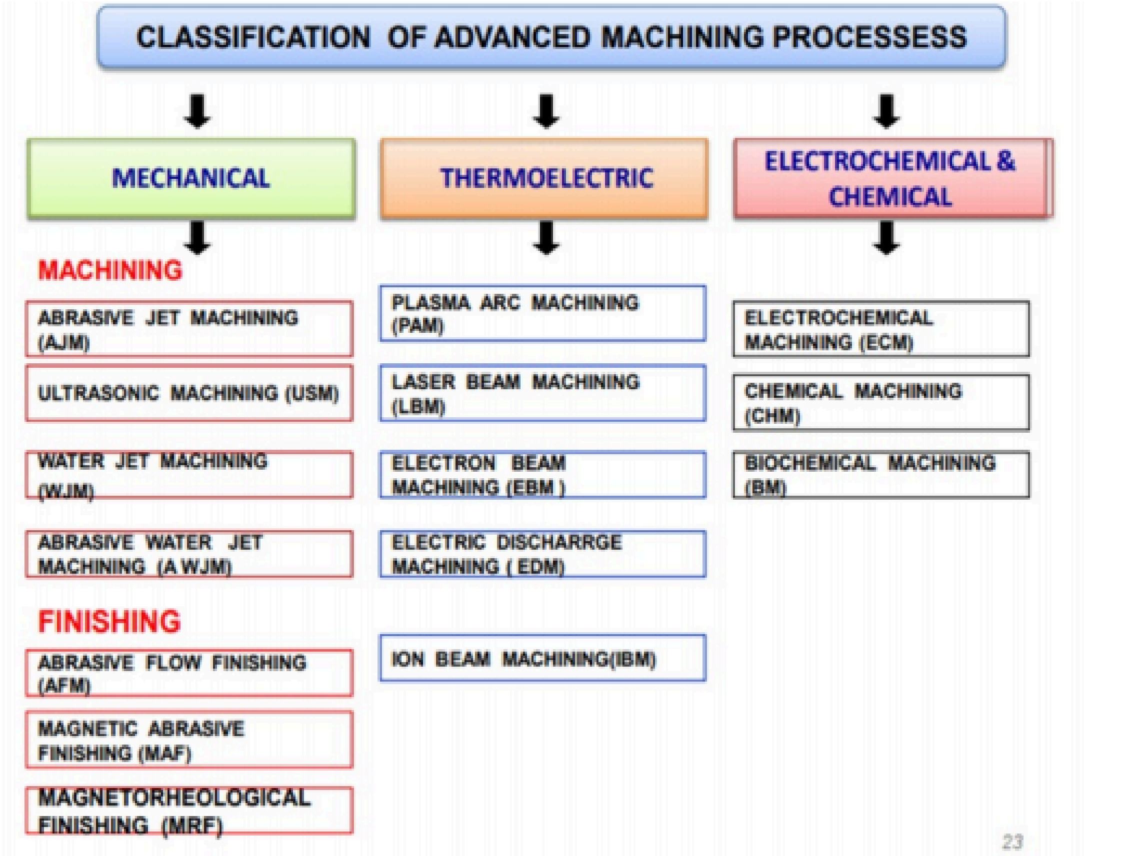
Mechanical : Erosion of the work material by a high velocity stream of abrasives or fluids (or both).

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 (metal particularly) are susceptible to chemical attack by certain acids or other etchants. In chemical machining, chemicals selectively remove material from portions of the work part, while other portions of the surface are protected by a mask.

Classification of AMPs,Based on the Kind of Energy used



Classifications of Conventional and Non – Conventional/Non – Traditional Process

S. No	Conventional Process	Non-Conventional Process
1	The cutting tool and work piece are always in physical contact with relative motion with each other, which results in friction and tool wear.	There is no physical contact between the tool and work piece, in some non-traditional process tool wear exists.
2	Material removal rate is limited by mechanical properties of work material.	NTM can machine difficult to cut & hard to cut materials like titanium, ceramics, nimonics, SST, composites, semiconducting materials.
3	Relative motion b/w the tool & work is typically rotary or reciprocating. Thus, the shape of work is limited to circular or flat shapes. In spite of CNC systems, production of 3D surface is still a difficult task.	Many NTM are capable of producing complex 3D shapes and cavities.
4	Machining of small cavities, slits, blind holes or through holes are difficult.	Machining of small cavities, slits and production of non-circular, micro sized,

		large aspect ratio, shall entry angle holes be using NTM.
5	Use relatively simple and inexpensive machinery and readily available cutting tools.	Nontraditional process requires expensive tools and equipment as well as skilled labor, which increase the production cost significantly.
6	Capital cost and maintenance cost is low.	Capital cost and maintenance cost is high.
7	Traditional process is well established and physics of process is well understood.	Mechanics of material removal of some of NTM process are still under research.
8	Conventional process mostly uses mechanical energy.	Most of NTM uses energy in direct form. E.g.:- Laser, Electron beam in its direct forms are used in LBM & EBM respectively.
9	Surface finish and tolerance are limited by machining inaccuracies.	High surface finish(up to 0.1 micron) and tolerance (25 Microns) can be achieved.
10	High material removal rate.	Low material removal rate.

Or

Conventional	**Un Conventional**
1. There is always direct contact between the tool and work piece.	1. There is no direct contact between the tool and work piece.
2. Material Removal Rate(MMR) is high.	2. Material Removal Rate(MMR) is low.
3. Cannot machine inaccessible parts.	3. Can machine inaccessible part with greater accuracy.
4. Used to machine general class of material	4. Uses to machine High Strength to Weight ratio material used for advance industries .viz. aerospace, aeronautical etc.

Product Requirements

- Complex Shapes
- Machining in inaccessible areas
- Low tolerances (let 0.01mm)
- Better surface integrity (no surface defects, etc.)
- High surface finish (Nano level)
- Miniaturization of products (E.g. landline mobile, old computers and laptop, etc.)
- High MRR
- High production rate while processing difficult to machine.

- Low cost of production
- Precision and ultraprecision machining
- Requires material removal in the form of atoms and /or molecules.

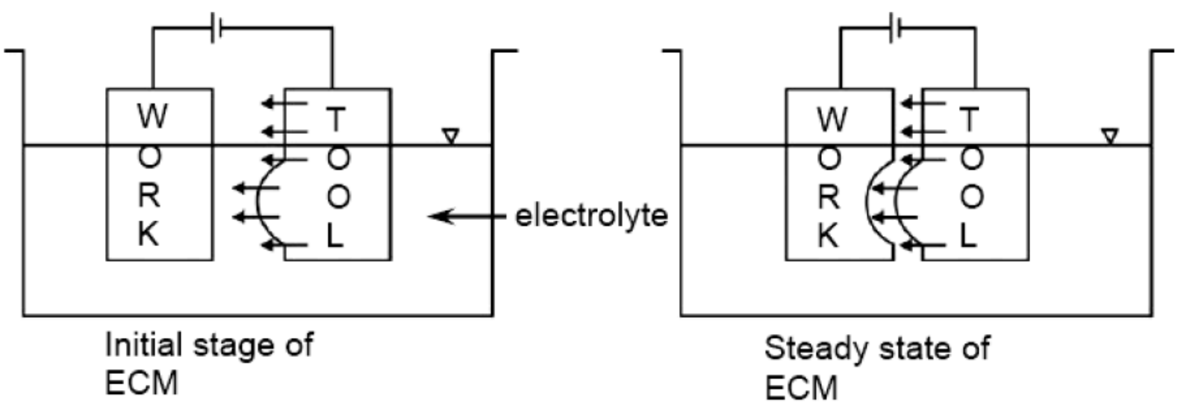
Electrochemical machining

Electrochemical machining is one of the most unconventional machining processes.

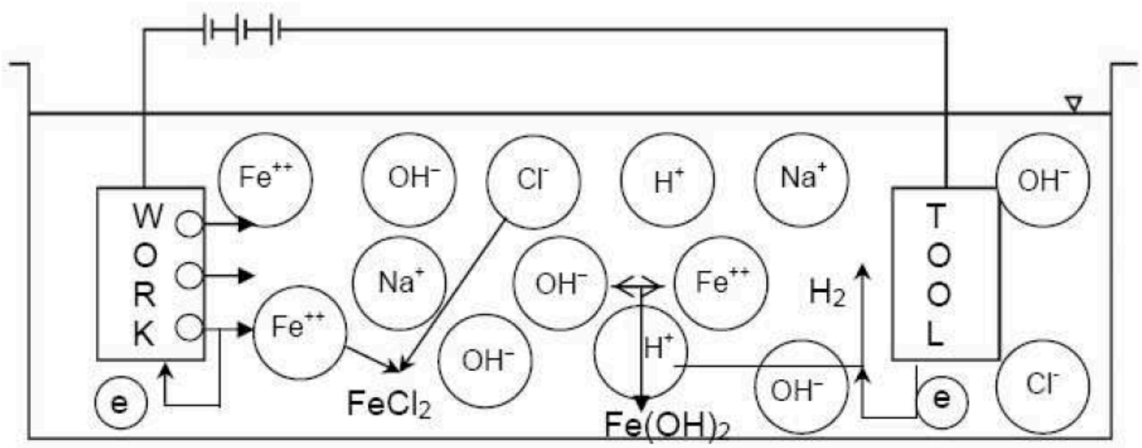
- The process is actually the reverse of electroplating with some modifications.
- It is based on the principle of electrolysis.
- In a metal, electricity is conducted by free electrons but in a solution the conduction of electricity is achieved through the movement of ions.
- Thus, the flow of current 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.***
- 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.
- 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.
- 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.
- ECM can be thought of a controlled anodic dissolution at atomic level of the work piece that is electrically conductive by a shaped tool due to flow of high current at relatively low potential difference through an electrolyte which is quite often water based neutral salt solution.
- **Electrical energy is used to produce a chemical reaction,** therefore, the machining process based on this principle is known as Electrochemical machining (ECM).
- This process works on the principle of **Faraday's laws of electrolysis**.
- Michael Faraday discovered that if the two electrodes are placed in a bath containing a conductive liquid and **DC potential (5-25V)** is applied across them, metal can be depleted from the anode and plated on the cathode This principle was in use for long time.
- Reverse of electroplating
- Mechanism of metal removal: Ion Displacement
- 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.
- 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.
- Work holding devices are made up of non conductivity material.

Schematic of Process



Chemistry of Process



Working principle of 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 electrochemical **machining of steel**, generally a neutral salt solution of **sodium chloride (NaCl)** is taken as the electrolyte.

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

$$NaCl \leftrightarrow Na^{+} + Cl^{-}$$

$$H_2O \leftrightarrow H^{+} + (OH)^{-}$$

- As the potential difference is applied between the work piece (anode) and the tool (cathode), **the positive ions move towards the tool and negative ions move towards the workpiece.**
- Thus, the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

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

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

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

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

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

- In practice $FeCl^2$ and $Fe(OH)^2$ would form and get precipitated in the form of sludge
- The ferrous hydroxide may react further with water and oxygen to form ferric hydroxide, Fe(OH)3.

4Fe(OH)2 + 2H2O + O2 → 4Fe(OH)3

Process Parameters

S. No	Parameters	Values
1	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
2	Electrolyte	
	Material	NaCl and $NaNO_3$
	Temperature	20 to 50 C
	Flow Rate	20 lpm/100 A current
	Pressure	0.5 to 20 bar
	Dilution	100 g/l to 500 g/l
3	Working Group	0.2 mm to 1 mm
4	Overcut	0.2 mm to 3 mm
5	Feed Rate	0.5mm/min to 15 mm/min
6	Electrode Material	Copper, Brass and bronze
7	Surface Roughness (Ra)	0.2 to 1.5 micro m(miu m)

Physical Parameters of the Non - Conventional

Parameters	ECM
Potential (V)	10

Current (Amp)	10000(D.C)
Power (W)	100000
Gap (mm)	0.20
Medium	Electrolyte

Power Consumption vs Metal Removal Rate For ECM

10^5, watts – 10^4 mm^3/min

Material Application

Metal Alloys					
Process	Aluminum	Steel	Super Alloy	Titanium	Refractory Material
ECM	Fair	Good	Good	Fair	fair

Non - Metals			
Process	Ceramics	Plastic	Glass
ECM	Not possible because its done only for material which has good electric conductivity.		

Process Capabilities

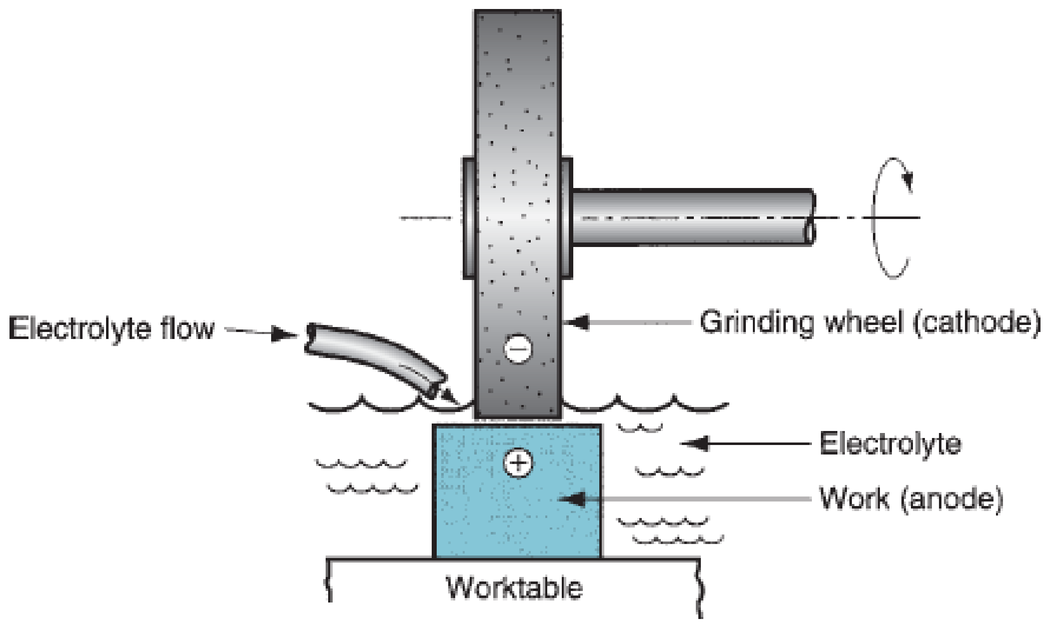
Process	**MRR(mm^3/min)**	**Tolerance(μ)**	**Surface (μ) CLA**	**Depth of surface damage (μ)**	**Power (watts)**
ECM	15000	50	0.1-2.5	5.0	100000

Economy

Process	**Capital cost**	**Tooling cost**	**Power consumption cost**	**Material removal rate efficiency**	**Tool wear**
ECM	Very High	Medium	Medium	Low	Very Low

Electrochemical grinding

- **Electrochemical grinding** is a process that removes electrically conductive material by grinding with a negatively charged abrasive grinding wheel, an electrolyte fluid, and a positively charged work piece.
- Electrochemical grinding and electrochemical machining are similar but a wheel is used instead of a tool shaped like the contour of the work piece.


Electrolyte flow
Grinding wheel (cathode)
Electrolyte
Work (anode)
Worktable

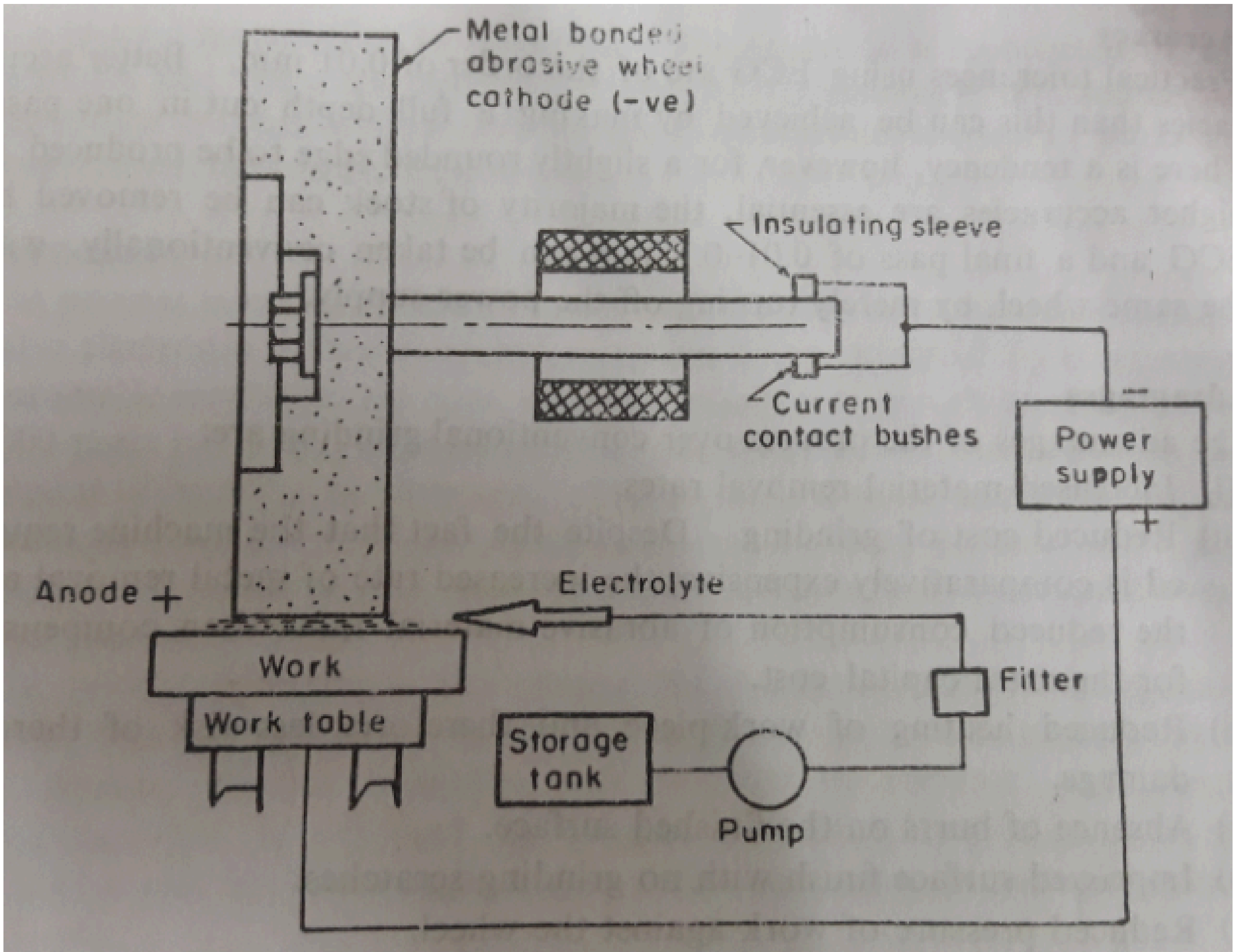


Fig. 3.10 Schematic of electrolytic grinding process

Process Characteristics

- The wheels and work piece are electrically conductive.
- Wheels used last for many grindings - typically 90% of the metal is removed by electrolysis and 10% from the abrasive grinding wheel.
- Capable of producing smooth edges without the burrs caused by mechanical grinding.
- Does not produce appreciable heat that would distort work piece.
- Decomposes the work piece and deposits them into the electrolyte solution. The most common electrolytes are sodium chloride and sodium nitrate.

Material Removal

- Most of the material removal is by electrochemical action.
- Some of the metal is mechanically removed by abrasive which is in contact with work piece.
- Practical MRRs are of the order of 1.0cm^3/min/100A.

Advantages of Electro Chemical Grinding

- Increased MRR
- Reduced cost of grinding
- Reduced heating of work piece
- Absence of burrs on the finished surface
- Improved surface finish with no grinding scratches
- Reduced pressure of work against the wheel

Chemical and Photo-Chemical machining

Chemical Machining

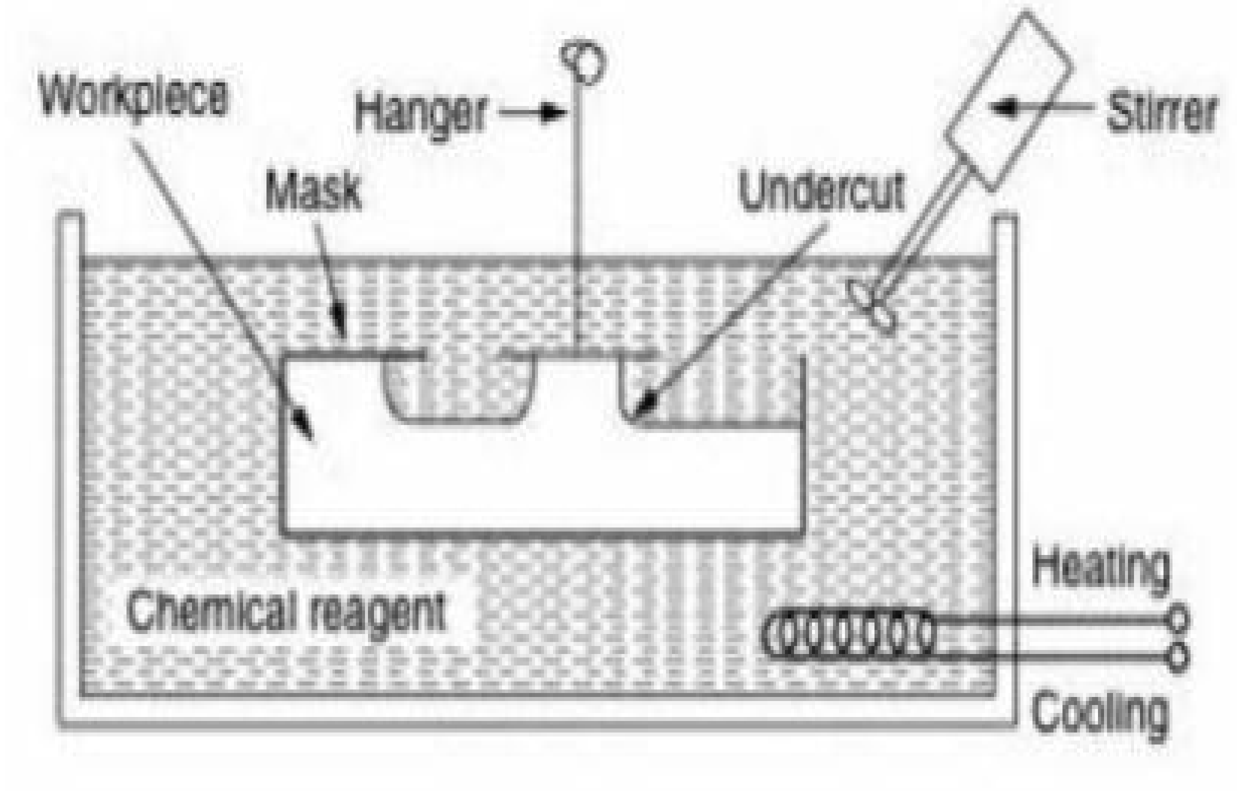
Principle

- Chemical machining is the process wherein material removal is accomplished by a chemical reaction.
- It is a controlled chemical dissolution of work-piece by contact with strong acidic or alkaline chemical reagent.

Process

Chemical machining process includes following steps:-

1. Pre-cleaning
2. Masking
3. Scribing – expose the job
4. Etching
5. Cleaning & removing masking material
6. Inspection



***1.*PreCleaning**

- To remove oil, grease, dirt, rust, or any other foreign particle present on the surface of the work-piece.
- Such foreign particles may lead to unnecessary or unwanted reaction products which lead to lower MRR and improper work-piece geometry.
- Pre-cleaning also leads to good adhesion of the masking material with the work-piece surface.

2.Masking

- Next step is the coating of the cleaned surface with the masking material.
- Masking materials impose chemical resistant for the etchant.
- **Vinyl, neoprene and butyl base materials are generally used as masking materials.**
- The selection of the maskants depends upon the

1. Chemical resistance required
2. Detail or resolution required
3. Ease of removal
4. Economics

3.Etching

- This stage is carried out in an immerse type etching machine.
- Work piece is immersed in the selected etchant for specific time period (as for required MRR).
- Uncovered surfaces are machined as chemical reaction starts.
- Work-piece is constantly rinsed (with help of stirrer) so as to avoid reaction products to settle onto machined surface.
- Etching process maybe carried out at elevated temperatures as required by the etchant.
- **For aluminum machining $FeCl_3$ is used.**

4.Cleaning

- After the etchant action is complete, cleaning & removing of masking material is carried out.

5.Inspection

- After cleaning, the work piece is sent for quality check.

Maskants

- Masking materials are called as maskants.
- It is used to protect the work piece surface from chemical etchant.
- Polymer or rubber-based materials are generally used as etchant.
- The selected material should have the following properties:-

1. Tough to withstand handling.
2. Well adhering to work piece surface
3. Easy scribing
4. Inert to chemical reagent used
5. Able to withstand heat used during chemical machining.
6. Easy removal after etching process.

Advantages

- Several parts can be machined simultaneously.
- Can be applied irrespective of hardness or conductivity of work-material.
- Surface finish obtained is of 0.5-2 microns.
- Low cost of operation
- Etchant can be reused
- Ease of operation

Disadvantages

- "Metal thickness to be machined is limited." or "chemical penetration required is limited"
- MRR is very low.
- Sharp corners can't be acted upon.
- Safety of operator from any chemical spill.
- Storage of etchant is another problem.
- Safety from production of harmful gases or any bi-product.

Photochemical Machining

Principle

- Its principle is the same as chemical machining, where material removal takes place due to chemical reaction between work material surface and an etchant.
- **Photochemical machining** (**PCM**), also known as **photochemical milling** or **photo etching**, is a chemical machining process used to fabricate **sheet metal** components using a **photoresists** and etchants to corrosively machine away selected areas.
- Photoresists are combination of photo-films and masking materials. Photofilms contains negative images of the parts (the area that will become the parts is clear and all of the areas to be etched are black).
- These negative imprints are developed on CAD software.
- When processed under UV light there imprints are generated onto masking material. Which is then peeled off at desired places so as to cause etching action to take place.

Process

- PCM is a process of selectively removing material by using a chemical action. The process begins with cleaning the material of all debris, grease, and other any contaminants; proper metal preparation is essential to the quality of the final product.
- Once it is fully cleaned, it is then coated with a photosensitive film and etchant resistant, used for cutting the metal, reducing the surface contamination and oxidation.
- Dry film is applied to both sides of the work piece to allow etching of both sides simultaneously.
- The photosensitive coating is then exposed to a UV light, which transfers the photo tool image onto the coated material.
- Then the material is developed (or cutting of masking from places where machining is to take place). During this process any material not protected by the resist is eroded.
- Once the material is processed, you are left with a metal sheet with the image of the design protected by the photo resist.
- The material is then stripped of the protective coating to produce your part.
- Before shipping, finished parts are inspected by a variety of our inspection equipment to ensure it meets your exact specifications.

Unit II : Non-Traditional Machining Processes (Mechanical)

Classification of Modern Machining Processes

Type of energy	*Mechanism of metal removal*	*Transfer media*	*Energy source*	*Processes*
Mechanical	Erosion	High velocity particles	Pneumatic/ hydraulic pressure	AJM, USM, WJM
	Shear	Physical contact	Cutting tool	Conventional machining
Electrochemical	Ion displacement	Electrolyte	High current	ECM, ECG
Chemical	Ablative relation	Reactive environment	Corrosive agent	CHM
Thermoelectric	Fusion	Hot gases	Ionized material	IBM, PAM
		Electrons	High voltage	EDM
	Vapourization	Radiation	Amplified light	LBM
		Ion stream	Ionized material	PAM

Physical Parameters

Physical Parameters of the Non – Conventional Processes

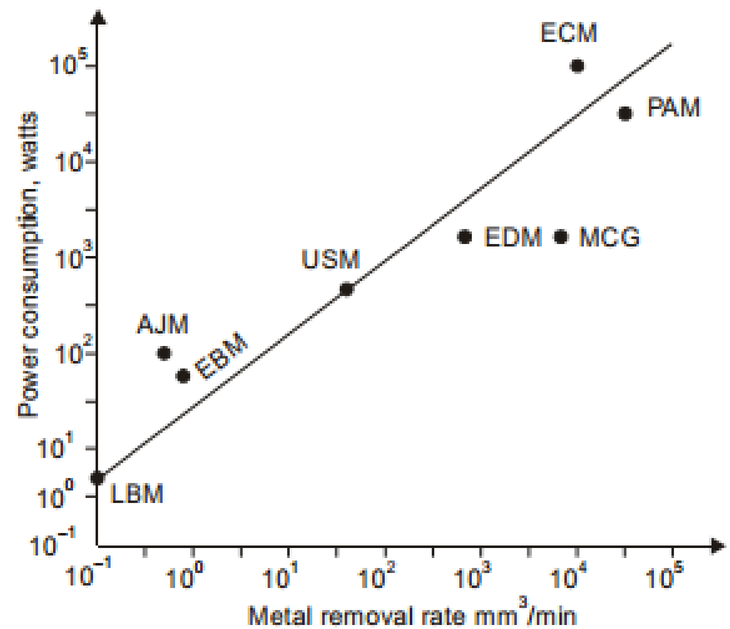
Parameters	**USM**	**AJM**	**ECM**	**CHM**	**EDM**	**EBM**	**LBM**	**PAM**
Potential (V)	220	220	10	-	45	150000	4500	100
Current (Amp)	12 (A.C.)	1.0	10000 (D.C.)	-	(Pulsed D.C.)	(Pulsed D.C.)	(Average 200 Peak)	(D.C.)
Power (W)	2400	220	100000	-	2700	150	-	50000
Gap (mm)	0.25	0.75	0.20	-	0.025	100	150	7.5
Medium	Abrasive in Water	Abrasive in gas	Electrolyte	Liquid Chemical	Liquid Dielectric	Vacuum	Air	Argon or Hydrogen (Inert gases)

MRR Due to	Crack initiation, propagation & brittle fracture of material.	Micro cutting action, brittle fracture of work material						
Commonly used tools	For tool holders **Titanium & Stainless steel**							
Tool materials	Ductile Material like **Brass, Stainless Steel or Mild Steel**.							

MRR due to

- In USM **crack initiation, propagation and brittle fracture of material.**
- In AJM **the high velocity abrasive particles remove the material by micro-cutting action as well as brittle fracture of the work material**

Power Consumption vs. Metal Removal Rate



Effect of metal removal rate on power consumption.

Shape to be Machined

Shape Application of Non – Conventional Processes

	Holes				Trough Cavities		Surfacing		Through Cutting	
Process	Precision small holes		Standard		Precision	Standard	Double contouring	Surface of revolution	Shallow	Deep
	Dia <0.025 mm	Dia >0.025mm	Length <20mm	Length >20mm						
USM	-	-	Good	Poor	Good	Good	Poor	-	Poor	-
AJM	-	-	Fair	Poor	Poor	Fair	-	-	Good	-
ECM	-	-	Good	Good	Fair	Good	Good	Fair	Good	Good
CHM	Fair	Fair	-	-	Poor	Fair	-	-	Good	-
EDM	-	-	Good	Fair	Good	Good	Fair	-	Poor	-
LBM	Good	Good	Fair	Poor	Poor	Poor	-	-	Good	Fair
PAM	-	-	Fair	-	Poor	Poor	-	Poor	Good	Good

Material Application

Metal Alloys					
Process	**Aluminum**	**Steel**	**Super Alloy**	**Titanium**	**Refractory Material**

ECM	Fair	Good	Good	Fair	fair
USM	Poor	Fair	Poor	Fair	Good
AJM	Fair	Fair	Good	Fair	Good
CHM	Good	Good	Fair	Fair	Poor
EDM	Fair	Good	Good	Good	Good
EBM	Fair	Fair	Fair	Fair	good
LBM	Fair	Fair	Fair	Fair	Poor
PAM	Good	Good	Good	Fair	Poor

Non - Metals			
Process	**Ceramics**	**Plastic**	**Glass**
ECM	Not possible because it's done only for material which has good electric conductivity.		
USM	Good	Fair	Good
AJM	Good	Fair	Good
CHM	Poor	Poor	Fair
EDM	Not possible because it's done only for material which has good electric conductivity.		
EBM	Good	Fair	Fair
LBM	Good	Fair	Fair
PAM	-	Poor	-

Process Capabilities

Process	**MRR(mm^3/min)**	**Tolerance(μ)**	**Surface (μ) CLA**	**Depth of surface damage (μ)**	**Power (watts)**
ECM	15000	50	0.1-2.5	5.0	100000
USM	300	7.5	0.5-1.2	25	2400
AJM	0.8	50	0.1-2.5	2.5	250
CHM	15	50	0.5-2.5	50	-
EDM	800	15	0.2-1.2	125	2700
EBM	1.6	25	0.5-2.5	250	150(average) 2000(peak)
LBM	0.1	25	0.5-1.2	125	2(average)
PAM	75000	125	Rough	500	50000
Conventional Machining	50000	50	0.5-5.0	25	3000

Economy

Process	**Capital cost**	**Tooling cost**	**Power consumption cost**	**Material removal rate efficiency**	**Tool wear**

ECM	Very High	Medium	Medium	Low	Very Low
USM	Low	Low	Low	High	Medium
AJM	Very Low	Low	Low	High	Low
CHM	Medium	Low	High*	Medium	Very Low
EDM	Medium	High	Low	High	High
EBM	High	Low	Low	Very High	Very Low
LBM	Low	Low	Very Low	Very High	Very Low
PAM	Very Low	Low	Very Low	Very Low	Very Low
MCG	Low	Low	Low	Very Low	Low

*indicates cost of chemicals.

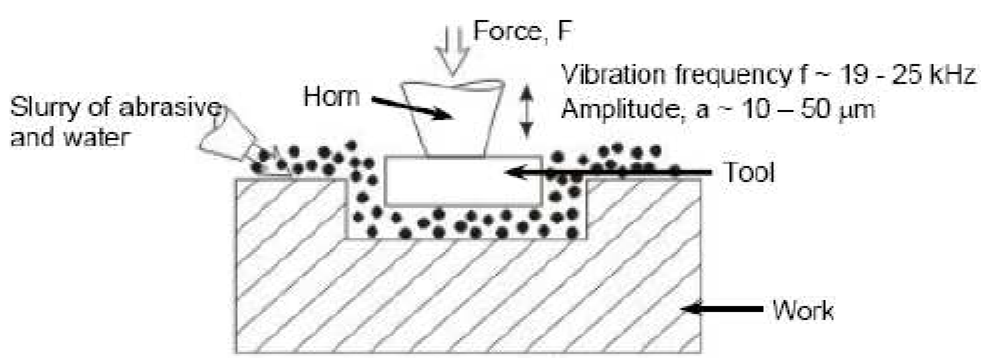
Ultrasonic Machining

Ultrasonic machining is a mechanical type non-traditional machining process employed to machine hard and brittle materials (both electrically conductive and non-conductive material) using an axially oscillating tool at ultrasonic frequencies [18–25 kilohertz (kHz)].

Or

USM is a process in which a cutting tool oscillates at **high frequency (about 20,000 cps)** in an abrasive slurry. The tool has the same shape as the cavity to be machined. The high-speed oscillations of the tool **drive the abrasive grain across a small gap of about 0.02 – 0.10 mm against the workpiece**. The impact of the abrasive is uniquely responsible for the material removal. The method is chiefly employed to machine hard and brittle materials which are either electrically conducting or non-conducting.

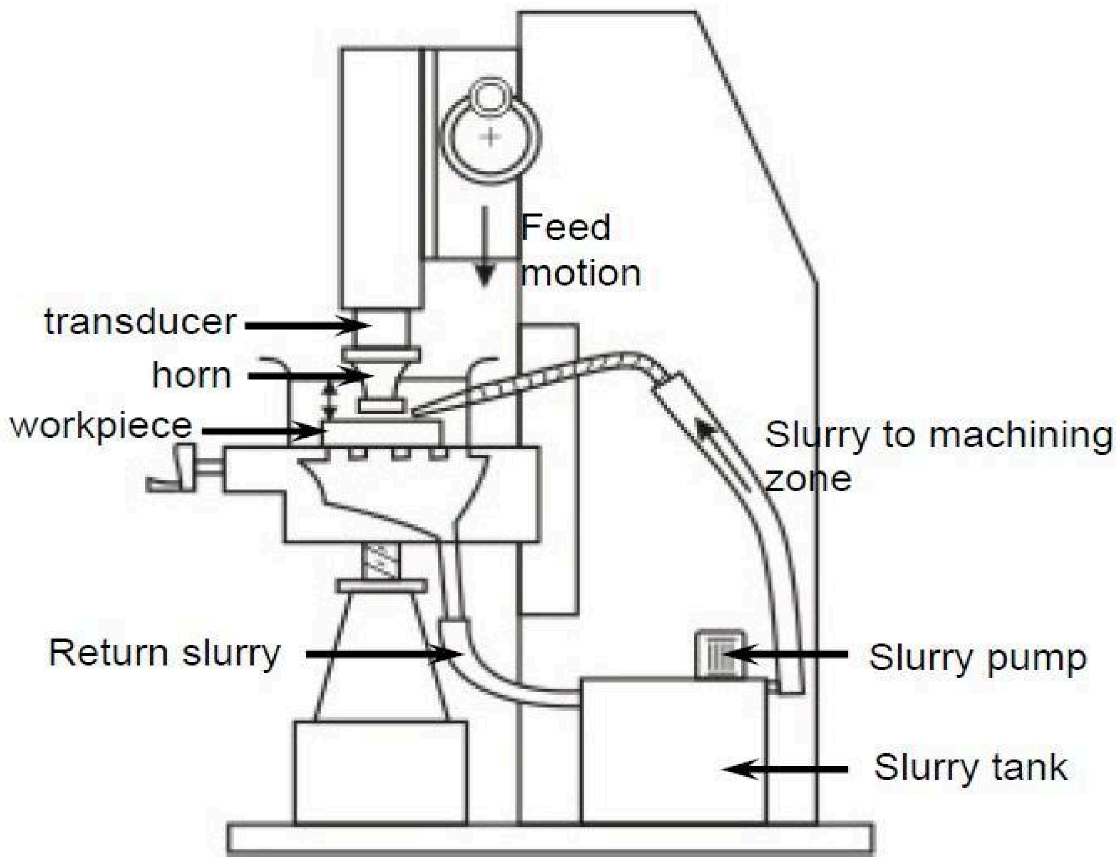
Tool oscillating range 10 – 50 microns



Working Principle

- The machining zone (between the tool and the work piece) is **flooded with hard abrasive particles** generally in the form of **water-based slurry**.
- As the tool vibrates over the work piece, abrasive particles act as indenter and indent both work and tool material .
- Abrasive particles , as they indent , the work material would remove the material from both tool and work piece.

- In Ultrasonic machining **material removal is due to crack initiation, propagation and brittle fracture of material.**



Elements of USM Process

- **High power sine wave generator:** This unit converts **low frequency (60 Hz)** electrical power to **high frequency (20kHz)** electrical power.
- **Ultrasonic Transducer:** The **high frequency electrical signal is transmitted to transducer which converts it into high frequency low amplitude vibration**. Essentially **transducer converts electrical energy to mechanical vibration.** There are two types of transducer used: Piezo electric transducer and Magneto-strictive transducer.
- **Tool holder OR Horn:** The tool holder holds and connects the tool to the transducer. It virtually transmits the energy and in some cases, amplifies the amplitude of vibration. **Material of tool should have good acoustic properties, high resistance to fatigue cracking. Commonly used tool holders are Titanium, Stainless Steel.**
- **Tool:** Tools are **made of relatively ductile materials like Brass, Stainless steel or Mild steel** so that Tool wear rate (TWR) can be minimized.
- **Piezo electric transducer:** These transducers generate a small electric current when they are compressed. Also, when the electric current is passed though crystal it expands. When the current

is removed, crystal attains its original size and shape. **Such transducers are available up to 900 Watts. Piezo electric crystals have high conversion efficiency of 95%.**

- **Magneto-strictive transducer:** These also changes its length when subjected to strong magnetic field. **These transducers are made of nickel, nickel alloy sheets. Their conversion efficiency is about 20-30%. Such transducers are available up to 2000 Watts**. The maximum change in length can be achieved is about 25 microns.
- **Abrasive slurry: Aluminum Oxide, Boron Oxide, Silicon Carbide, Diamond Powder**
- **Liquid Media:** Abrasives are suspended in liquid media for given functions
    - Acts as an bond between the work piece and the tool
    - Helps efficient transfer of energy between work piece and tool
    - Acts as a coolant
    - Helps to carry away the worn abrasive away from machining zone
- **Characteristics:**
    - Density
    - Good wetting properties
    - High thermal conductivity and specific heat
    - Low viscosity
    - Non-corrosive
- **Water** is most commonly used media in USM, while benzene, glycerol, and oils are alternatives

Material Removal Models in USM

Theoretical analysis and experimental results have revealed that **USM is a form of abrasion and material removal in the form of small grains** by following mechanisms

Throwing of abrasive grains

Hammering of abrasive grains

Chemical erosion due to micro –agitation

Abrasive particles are assumed to be spherical in shape having diameter d. Abrasive particles move under high frequency vibrating tool. There are two possibilities when the tool hit the particle.

- If the size of the particle is small and gap between the tool and work is large, then particle will be thrown by tool to hit the work piece.
- If the size of the particle is large and gap between tool and work is small, then particle is hammered over the work surface.

Process Parameters

- Amplitude of vibration (15 to 50 microns)
- Frequency of vibration (19 to 25 kHz).
- Feed force (F) related to tool dimensions
- Feed pressure
- Abrasive size : 15 µm – 150 µm
- Abrasive material: Al_20, SiC, Boron silicarbide, Diamond.
- Contact area of the tool
- Volume concentration of abrasive in water slurry

Effects of Parameters

1. Effect of Amplitude on MRR

- Increase in amplitude of vibration increases MRR. **(Amplitude increases = MRR increases)**
- To maximize the amplitude of vibration concentrator should operate at resonance frequency.

2.Effect of Frequency on MRR

- Frequency has significant effect on MRR. Frequency used for machining process must be resonant frequency to obtain the greatest amplitude at the tool tip and thus achieve the maximum utilization of the acoustic system.

3.Effect of Abrasive Grain Size & Velocity

- An increase in abrasive grain size results in higher MRR but poorer surface finish. **(Abrasive grain size increases = MRR increases = Poor Surface finish)**
- Maximum MRR is achieved when abrasive grain size is comparable with amplitude of vibration of the tool.

4.Effect of Applied Static Load (Feed Force)

- MRR increase with the feed force.
- Surface finish is found to be little affected by the applied static load.
- Higher loads, contrary to expectations, do not give a rougher finish. Surface finish, in fact, improves because the grains are crushed to small size with higher loads.

5.Effect of Slurry, Tool and work Material

- MRR increases with slurry concentration. **Slurry saturation occurs at 30 to 40% abrasive/water mixture.**

- The pressure with which the slurry is fed into the cutting zone affects MRR **in some cases MRR can be increased even ten times by supplying the slurry at increased pressure. (Supply of Slurry increases = MRR increases)**
- Material Removal rate drops with increasing viscosity. **(Viscosity increases = MRR decreases)**
- The shape of the tool affects the MRR. **Narrower rectangular tool gives more MRR compared to square cross section**. **Conical tool gives twice MRR compared to cylindrical tool**.

Process Capability

- **Can Machine work piece harder than 40 HRC to 60 HRC like carbides, ceramics, tungsten glass** that cannot be machined by conventional methods
- **Tolerance range 7 micron to 25 microns**
- Holes up to 76 microns have been drilled hole depth up to 51mm have been achieved easily. Hole depth of 152mm deep is achieved by special flushing techniques.
- **Linear material removal rate -0.025 to 25mm/min**
- **Surface finish -0.25 micron to 0.75 micron**
- Non directional surface texture is possible compared to conventional grinding
- Radial over cut may be as low as 1.5 to 4 times the mean abrasive grain size.

Applications

- Machining of cavities in electrically non-conductive ceramics
- Used to machine fragile components in which otherwise the scrap rate is high
- Used for machining hard, brittle metallic alloys, semiconductors, glass, ceramics, carbides etc.
- Used for machining round, square, irregular shaped holes and surface impressions
- USM enables a dentist to drill a hole of any shape on teeth without any pain.
- Round holes and holes of any shape for which a tool can be made. The range obtainable shapes can be increased by moving the workpiece during cutting.
- Coining operations for materials such as glass, ceramics, etc.
- Threading by appropriately rotating and translating the workpiece/tool.

Advantages

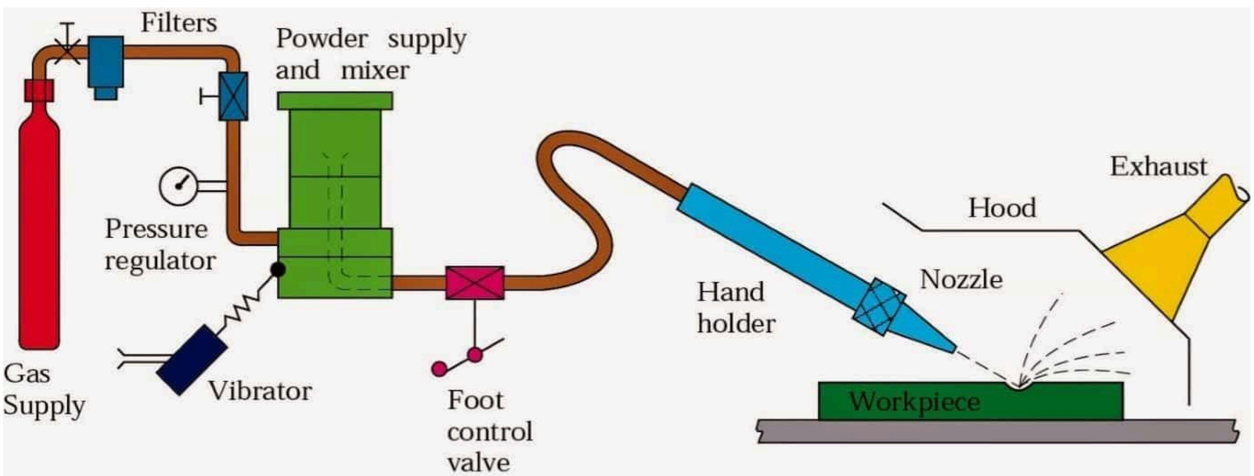
- No heat is generated in work, therefore no significant changes in physical structure of work material
- It can be used machine hard, brittle, fragile and non - conductive material
- It can be adopted in conjunction with other new technologies like EDM,ECG,ECM.
- It is burr less and distortion less processes.

Disadvantages

- Low Metal removal rate
- It is difficult to drill deep holes, as slurry movement is restricted
- Tool wear rate is high due to abrasive particles. Tools made from brass, tungsten carbide, MS will wear from the action of abrasive grit.
- USM can be used only when the hardness of work is more than 45 HRC.

Abrasive Jet Machining

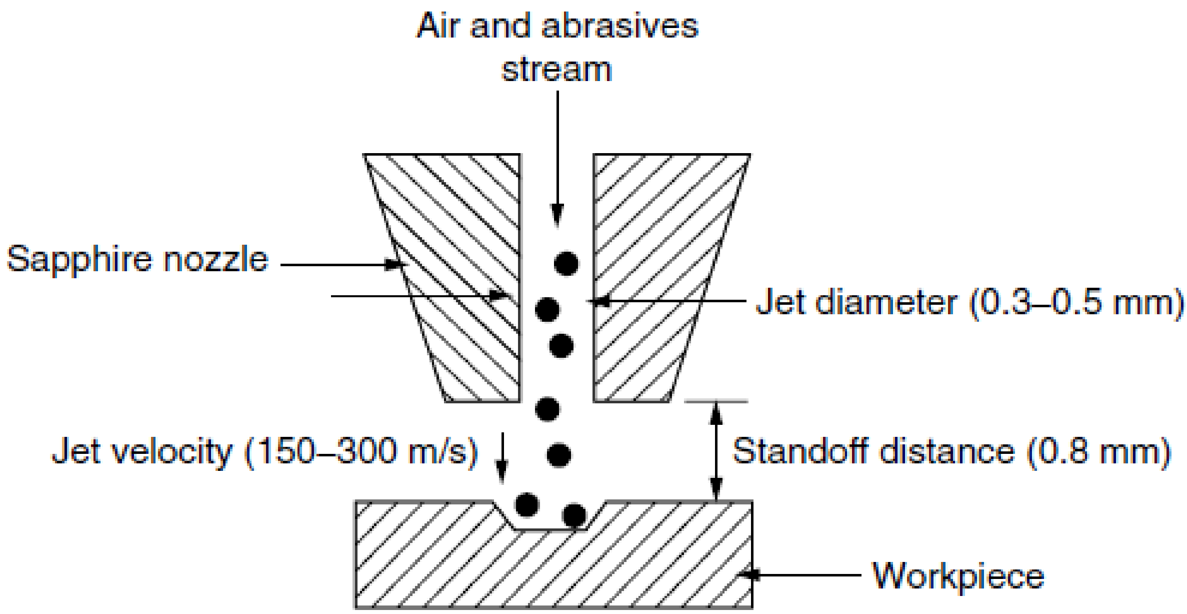
- In abrasive jet machining, a **focused stream of abrasive particles**, carried by high **pressure air or gas** is made to impinge on the work surface through **a nozzle**.
- The high velocity stream of abrasives is generated by **converting pressure energy of carrier gas or air to its kinetic energy** and hence high velocity jet.
- **The high velocity abrasive particles remove the material by micro-cutting action as well as brittle fracture of the work material.**



- This is a process of removal of material by impact erosion through the action of concentrated high velocity stream of grit abrasives entrained in high velocity gas stream.
- AJM is different from shot or sand blasting, as in AJM, finer abrasive grits are used and parameters can be controlled more effectively providing better control over product quality.

Process

- In AJM, generally, the abrasive particles of around **50 microns grit size** would impinge on the work material at **velocity of 200 m/s from a nozzle of ID 0.5mm** with a **standoff distance of around 2mm.**
- The kinetic energy of the abrasive particles would sufficient to provide material removal due to brittle fracture of the work piece or even micro cutting by the abrasives.



Material Removal Mechanism

- Fine particles (0.025mm) are accelerated in a gas stream.
- The particle is directed towards the focus of machining.
- As the particles impact the surface, it causes a micro fracture, and gas carries fractured particles away.
- Brittle and fragile work better.

Material Removal rate/Metal Removal Rate in AJM

Sarkar and Pandey proposed a model for the computation of MRR in AJM.

$$Q = \text{alpha } Z\, d^3\, v^{3/2} (\rho/12\, H_w)^{3/4}$$

Z = no of particles impacting per unit time.

d = mean diameter of abrasive grains.

ρ = density of abrasive particles.

H_w = Hardness of work material.

V = velocity of abrasive grains.

Mass Ratio = ratio of abrasive mass flow rate and sum of abrasive carrier gas

Combined mass flow rate. Denoted by alpha.

Process Parameters

- **Abrasives**

a) material – Al2O3 SiC Glass beads Crushed glass Sodium bi carbonate

b) shape – irregular/regular

c) Size – 10 to 50 microns

d) Mass flow – 2-20 gm/min

- **Carrier Gas**

a) Composition – Air, CO2, N2

b) Density – 1.3 kg/m3

c) Pressure - 2 to 10 bar

d) Flow rate - 5 to 30 gm/min

- **Abrasive Jet**

a) Velocity - 150 to 300 m/s

b) Mixing ratio – Volume flow rate of abrasives/Volume flow rate of gas

c) Standoff distance – SOD- 0.5 to 15mm.

d) Impingement angle – 60 to 90 deg.

- **Nozzle**

a) Material – WC/Sapphire

b) Diameter – 0.2 to 0.8 mm

c) Life – 300 hours for sapphire, 20 to 30 hours for WC

Abrasives	Grain Sizes	Application
Aluminum Oxide (Al_2O_3)	12, 20, 50 microns	Good for cleaning, cutting and deburring
Silicon Carbide (SiC)	25, 40 microns	Used for similar application but for hard material
Glass Beads	0.635 to 1.27mm	Gives matte finish
Dolomite	200 mesh	Etching and polishing
Sodium bi Carbonate	27 micros	Cleaning, deburring and cutting of soft material Light finishing below 50`C

Variables in AJM/ Effects of Parameters

- **Effect of abrasive flow rate and grain size on MRR**: At a particular pressure MRR increase with increase of abrasive flow rate and is influenced by size of abrasive particles. But after reaching optimum value, MRR decreases with further increase of abrasive flow rate.
- **Carrier Gas**: **-** It should not flare excessively when discharged from nozzle into the work piece. **Should be non-toxic, easily available, cleaned without difficulty & capable of being dried. Air, CO2 and Nitrogen are used.**
- **Grain Size**- Generally ranges between 10 – 50 microns.
- Effect of exit gas velocity and abrasive particle density
- **Effect of Mixing ratio on MRR:** Increased mass flow rate of abrasive will result in a decreased velocity of fluid and will thereby decreases the available energy for erosion and ultimately the MRR. It is convenient to explain to this fact by term MIXING RATIO (M).
- **Standoff distance: Standoff distance is defined as the distance between the face of the nozzle and the work surface of the work. A large SOD results in flaring of jet which leads to poor accuracy.**

Process Capability

- Material removal rate – **0.015 cm^3/min**
- Narrow slots – 0.12 to 0.25mm ± 0.12mm
- Surface finish - **0.25 micron to 1.25 micron**
- Sharp radius up to 0.2mm is possible
- Steel up to 1.5mm, Glass up to 6.3mm is possible to cut
- **Machining of thin sectioned hard and brittle materials is possible**.

Applications

1. Drilling holes, cutting slots, cleaning hard surfaces, deburring, polishing, and radiusing.
2. Deburring of cross holes, slots, and threads in small precision parts that require a burr-free finish, such as hydraulic valves, aircraft fuel systems, and medical appliances
3. Machining intricate shapes or holes in sensitive, brittle, thin, or difficult-to-machine materials
4. Insulation stripping and wire cleaning without affecting the conductor
5. Micro-deburring of hypodermic needles
6. Frosting glass and trimming of circuit boards, hybrid circuit resistors, capacitors, silicon, and gallium
7. Removal of films and delicate cleaning of irregular surfaces because the abrasive stream is able to follow contours

Advantages

1. High surface finish can be obtained depending upon the grain sizes

Particle size (In microns)	Surface Roughness (In microns)
10	0.152 to 0.203
25 to 27	0.355 to 0.675
50	0.965 to 1.27

2. **Depth of damage is low (around2.5 microns)**
3. It **provides cool cutting action**, so it **can machine delicate and heat sensitive material**
4. Process is free from chatter and vibration as there is no contact between the tool and work piece
5. **Capital cost is low and it is easy to operate and maintain AJM**.
6. **Thin sections of hard brittle materials like germanium, mica, silicon, glass and ceramics can be machined.**
7. It has the capability of cutting holes of intricate shape in hard materials.

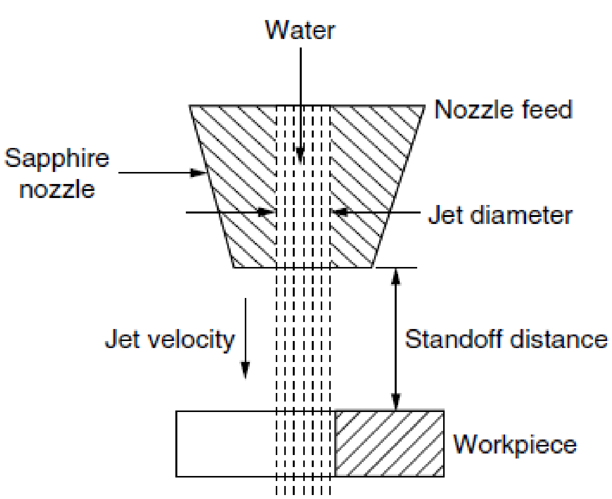
Disadvantages

1. Limited capacity due to low MRR. MRR for glass is 40 gm/minute
2. Abrasives may get embedded in the work surface, especially while machining soft material like elastomers or soft plastics.
3. The accuracy of cutting is hampered by tapering of hole due to unavoidable flaring of abrasive jet.
4. Stray cutting is difficult to avoid
5. A dust collection system is a basic requirement to prevent atmospheric pollution and health hazards.
6. Nozzle life is limited (300 hours)
7. Abrasive powders cannot be reused as the sharp edges are worn and smaller particles can clog the nozzle.
8. Short standoff distances when used for cutting , damages the nozzle.

Water Jet Machining

- **The key element in water jet machining (WJM) is a water jet, which travels at velocities as high as 900 m/s**.
- When the stream strikes a work piece surface, the erosive force of water removes the material rapidly.

- The water, in this case, acts like a saw and cuts a narrow groove in the work piece material.
- Hydrodynamic or Water Jet cutting (WJC)
- **High Pressure (400 MPA), High Velocity stream(900 m/s) from a nozzle opening of 0.1 to 0.4 mm diameter**
- **The nozzle unit consists of a holder made of stainless steel, and a jewel nozzle made of sapphire, ruby, or diamond**
- Filtration systems is used to separate the swarf produced during cutting.
- **Preferred cutting fluids are polymer solutions**, because of their tendency to produce a coherent 4 stream.
- *Standoff distance:* the separation between the nozzle opening and the work surface.
- generally desirable to be small to minimize dispersion of the fluid stream (typically 3.2 mm).
- **size of nozzle orifice affects the precision of cut**;
- smaller openings are used for finer cuts on thinner materials.
- thicker jet streams and higher pressures are required to cut thicker stock.
- **Typical feed rates range from 5 to 500 mm/s, depending on work material and its thickness**
- **Used for plastics, leather, textiles, composites, tile, carpet, cardboard etc.**
- **SOD RANGE 0.2 to 0.8 mm**

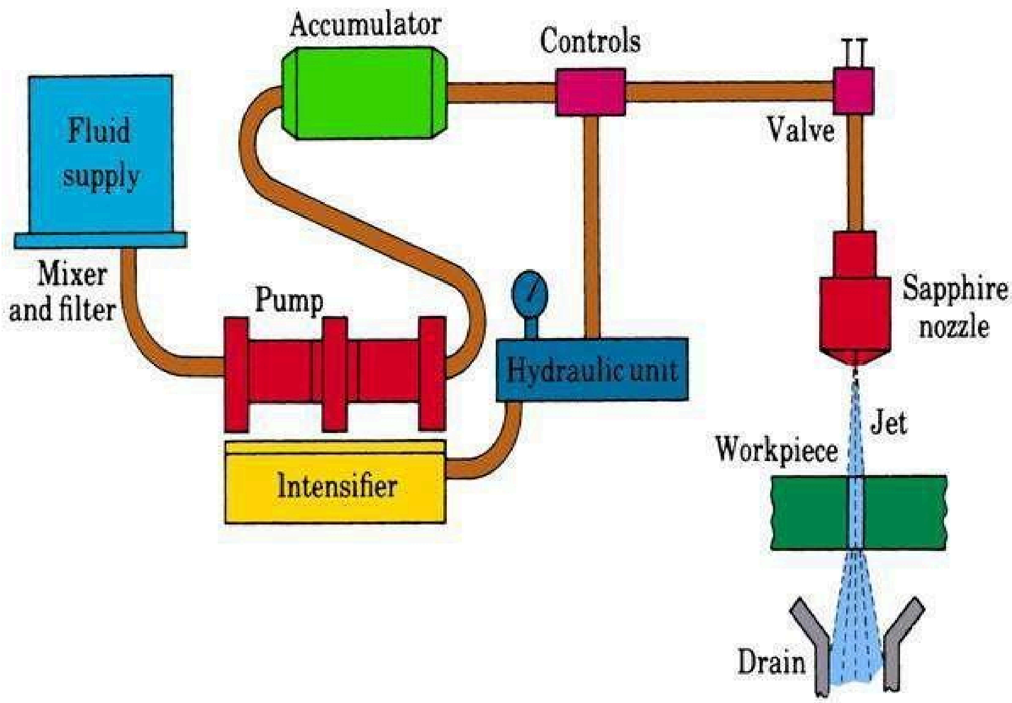


- **Jet cutting nozzle diameter 0.10 to 0.30mm**.
- Stand – off distance value ranges between 2.5 to 6 mm. **SOD = 2.5 – 6mm**
- Velocity of the water jet stream ranges between 540 to 1480 m/s. **Velocity = 540 – 1480 m/s**
- The material thickness value of work piece range between 0.8 to 25mm. **Thickness of Work piece = 0.8 – 25 mm**

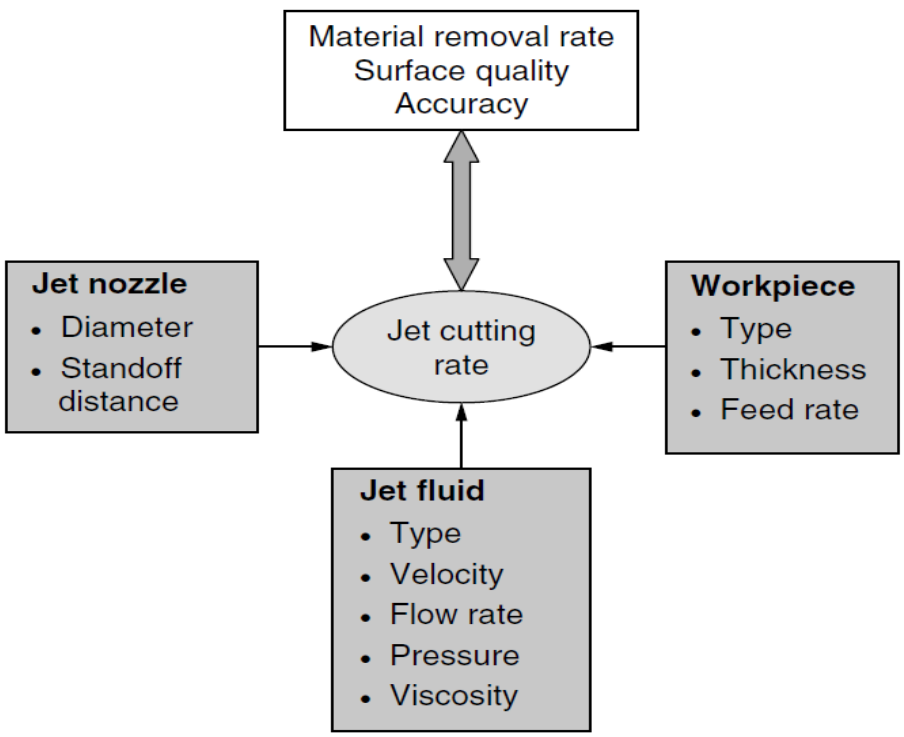
- In WJM, value of the feed rate ranges between 0.5 to 200 m/min. **Feed rate = 0.5 – 200 m/min**
- Velocity, flow rate, viscosity properties of jet fluid that affect the MRR.
- In the nozzle, outside temperature has no effect on the rate of material removal.

The Machining System

- Hydraulic Pump
- Intensifier
- Accumulator
- High pressure tubing
- Jet cutting nozzle
- Catcher
- **Hydraulic pump:** The hydraulic pump is powered from electric motor and supplies oil at pressures as high as to drive a reciprocating plunger pump termed an intensifier.
- **Intensifier:** The intensifier converts the energy from the low-pressure hydraulic fluid into ultrahigh-pressure water.
- **Accumulator:** The accumulator maintains the continuous flow of the high-pressure water and eliminates pressure fluctuations.
- **High-pressure tubing:** High-pressure tubing transports pressurized water to the cutting head.
- **Jet cutting nozzle:** The nozzle provides a coherent water jet stream for optimum cutting.
- **Catcher:** The catcher acts as a reservoir for collecting the machining debris entrained in the water jet. Moreover, it reduces the noise levels.



Material Removal Rate



Applications

- Cutting

- Drilling
- Machining of fiber-reinforced plastics
- Cutting of rocks
- Deburring
- Cutting of printed circuit boards
- Surface treatment

Advantages

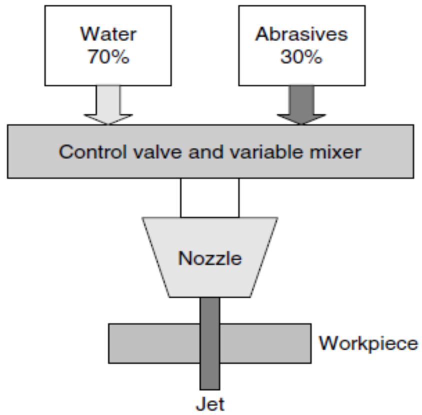
- It has multidirectional cutting capacity.
- No heat is produced.
- Cuts can be started at any location without the need for predrilled holes.
- Wetting of the workpiece material is minimal.
- There is no deflection to the rest of the workpiece.
- The burr produced is minimal.
- The tool does not wear and, therefore, does not need sharpening.
- The process is environmentally safe.
- Hazardous airborne dust contamination and waste disposal problems that are common when using other cleaning methods are eliminated.

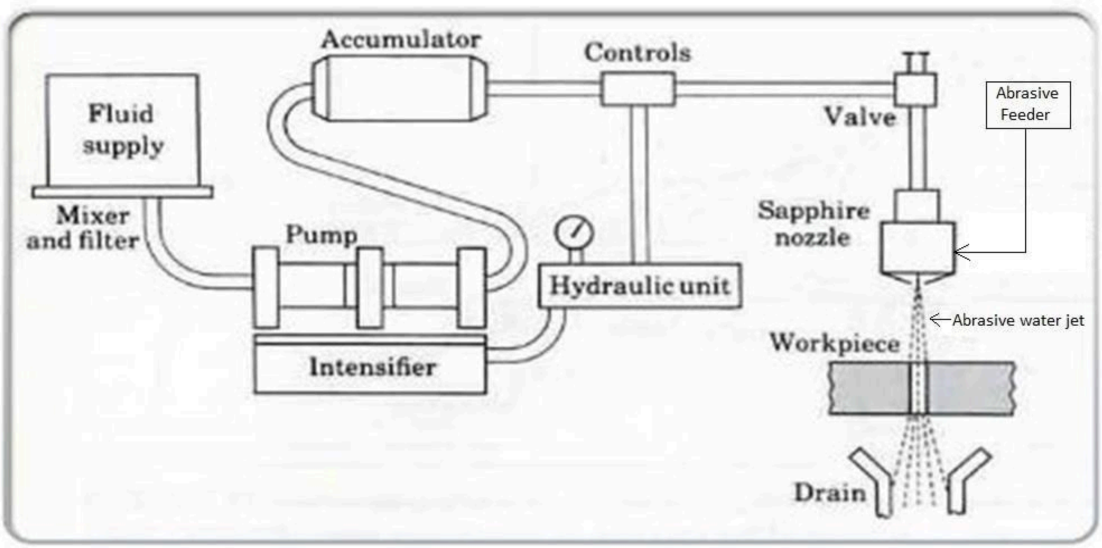
Disadvantages

- It is not suitable for mass production because of high maintenance requirements

Abrasive Water Jet Machining

- WJM is suitable for cutting plastics, rubber insulation, automotive carpeting, and most textiles.
- Harder materials such as glass, ceramics, concrete, and tough composites can be cut by adding abrasives to the water jet during abrasive water jet machining (AWJM).
- The addition of abrasives to the water jet enhanced the material removal rate and produced **cutting speeds between 51 and 460 mm/min.**





SCHEMATIC LAYOUT OF AWJM

Process

- A high pressure and high velocity water jet from high pressure water tube issues from the orifice.
- It then combines with the abrasive material (fed through the abrasive feeder hose) to form an abrasive water jet.
- Proper mixing of abrasive particles takes place inside the mixing tube and these abrasive particles gain the desired velocity inside the mixing tube only.
- Now after mixing and gaining of momentum, this abrasive water jet is made to strike the work material to start machining.
- **Machining starts with erosion and then carried further by material fracture.**

Components of AWJM

Pumping system:-

it comprises of hydraulic motor, pump and intensifier

1. Over here water at low pressure is converted to high pressure.
2. The motor, pump and intensifier are controlled through direction control valves.

Accumulator:-

3. to counter pressure drops in the intensifier an accumulator is provided to accumulate water at high pressure.
4. The release of water through accumulator is also controlled through direction control valves.

Nozzle:-

5. the high-pressure head water obtains direction and velocity in the nozzle only.
6. It comprises of **an orifice,** which is an opening of very small dia (**0.2-0.4mm).**
7. It converts high potential or **pressure head of water to high velocity head.**
8. A mixing tube is also installed with it, where mixing of abrasives and water jet takes pace.

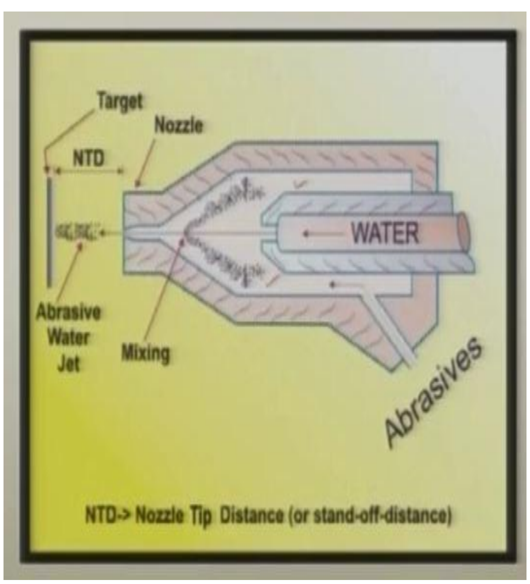
Types of Nozzle

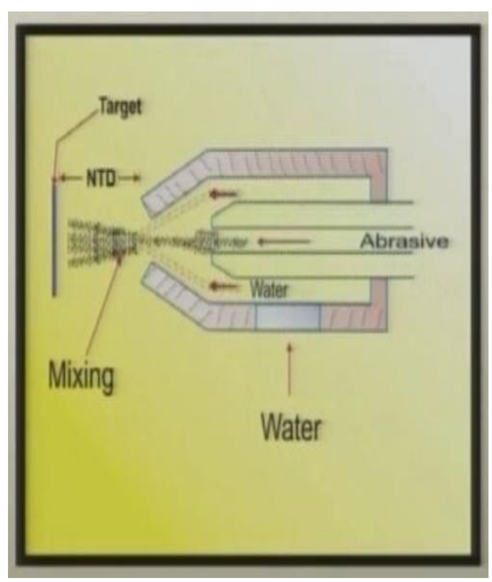
1. <u>Single jet side feed nozzle</u>:-

(a) Simple to construct but has high wear.

(b) Water jet flows through the center and abrasive particles are fed from the side.

(c) Mixing starts just at the inlet of mixing tube.





2. <u>Annular jet central feed nozzle</u>:-

(a) Abrasives are provided from the center of the nozzle and water jets flows over & around the nozzle in annular fashion, carrying with it abrasive particles also.

(b) It has less wear as mixing takes place outside the nozzle.

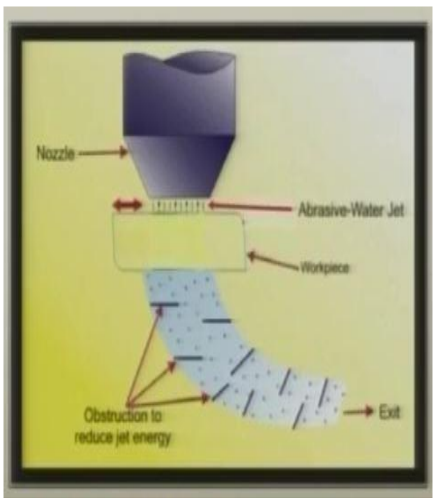
(c) Divergence of jet is more and thus it becomes less accurate and has low cutting.

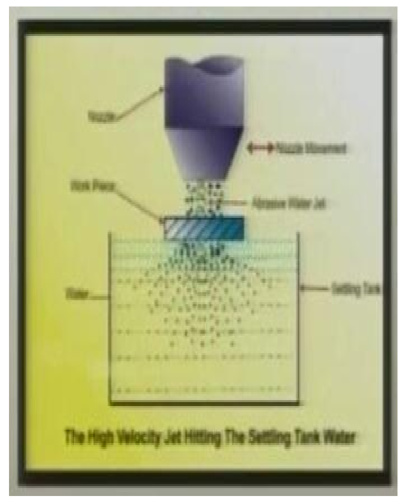
Catcher : The catcher acts as a reservoir for collecting the machining debris entrained in the Abrasive water jet. Moreover, it reduces the noise levels.

Types of Catchers

1. <u>When nozzle is stationery and work piece is moving</u>:-

- Over here obstructions are placed in the path of water jet. So that after striking these obstructions its velocity decreases considerably.





2. <u>When work piece is stationery and nozzle is moving</u>:-

- Over here, there is a stationary water filled settling tank. So the momentum the jet has even after cutting is dissipated into the water in the water tank.

Parameters

The general domain of parameters in entrained type AWJ machining system is given below:

• Orifice – Sapphires – 0.1 to 0.3 mm

• Focussing Tube – WC – 0.8 to 2.4 mm

• Pressure – 2500 to 4000 bar

• Abrasive – garnet, olivine, sand and glass beads

• Abrasive flow - 0.1 to 1.0 Kg/min

• Standoff distance – 1 to 2 mm

• Machine Impact Angle – 60^{o} to 90^{0}

• Traverse Speed – 100 mm/min to 5 m/min

• Depth of Cut – 1 mm to 250 mm

Applications

• Cleaning

• Cutting soft materials

• Textile, Leather industry

• Cutting

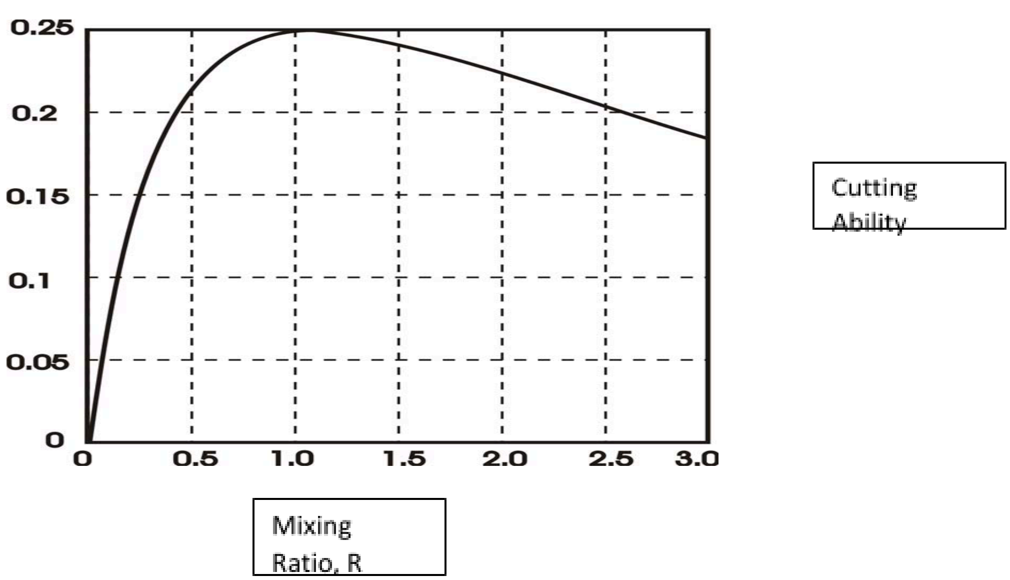
• Milling

• Drilling

• Turning, etc.

Advantages

- No dust
- High cutting speed
- No fire hazards
- High edge quality
- No vibration
- Grinding and polishing are eliminated.
- As no heat is generated during machining therefore physical properties of material remain intact.



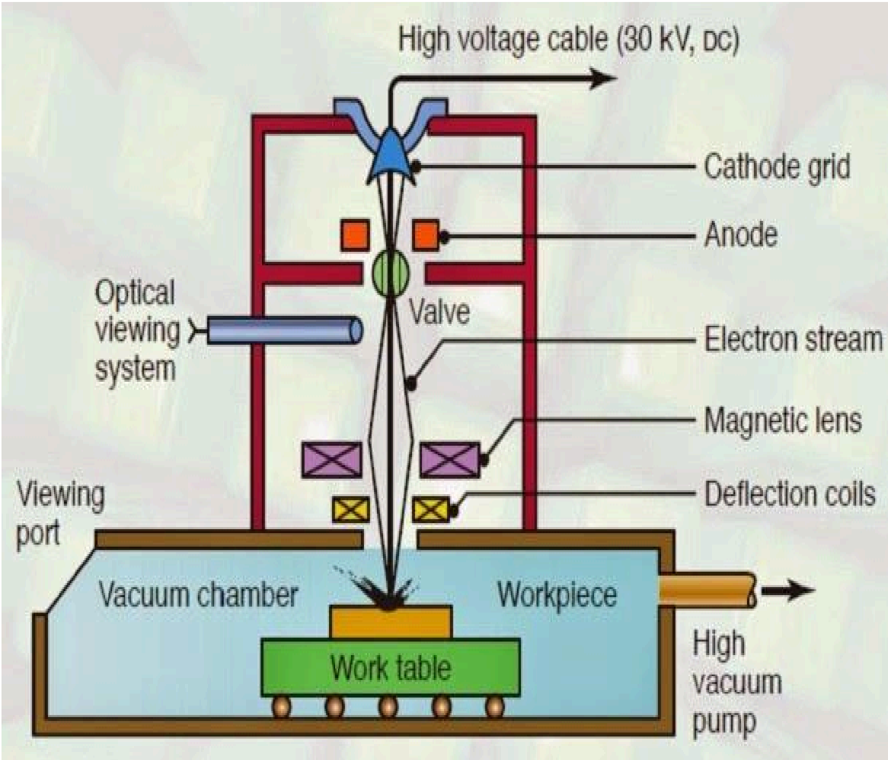
Disadvantages

- Taper

- Thin sections can be only cut.
- Limited materials could be only cut as when it comes to tool steels its cutting effect reduces considerably.
- Difficult to construct the nozzle and it wear is another problem.
- Stream lag gives poor surface finish.

Unit III : Non - Traditional Machining Processes (Thermal)

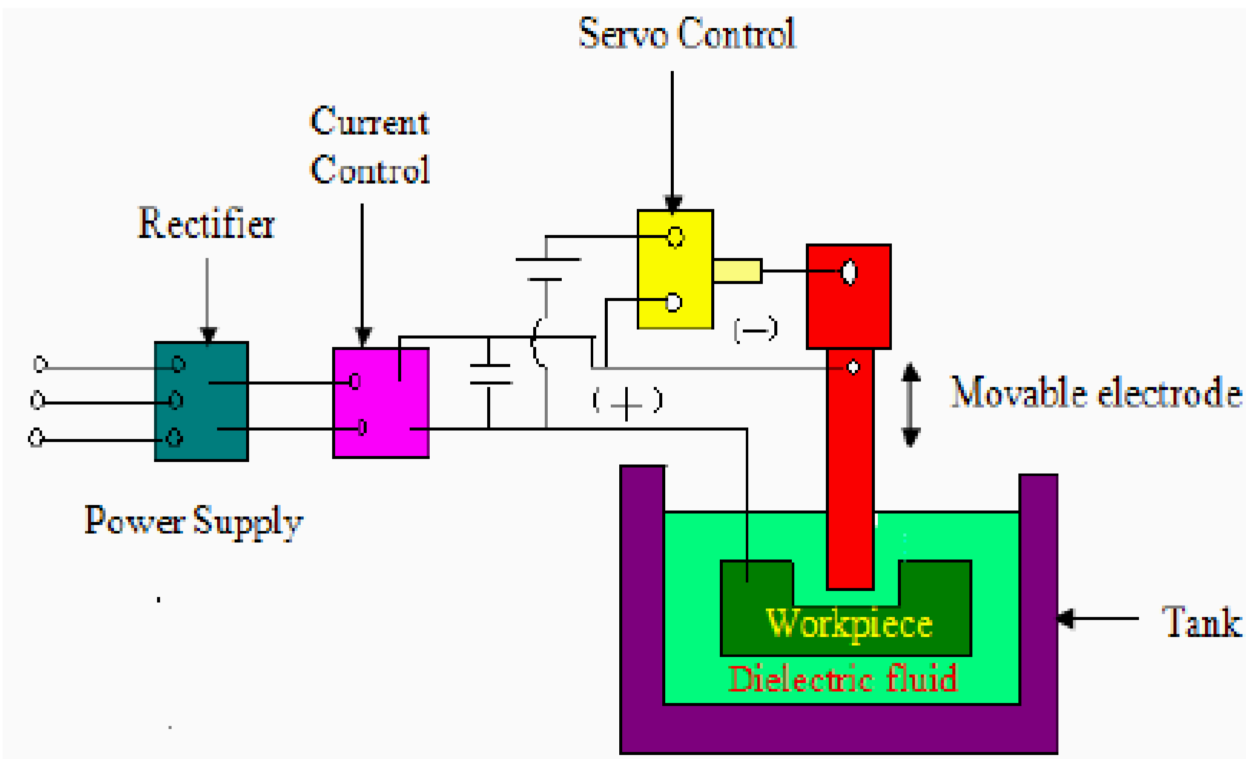
Electric Discharge Machining



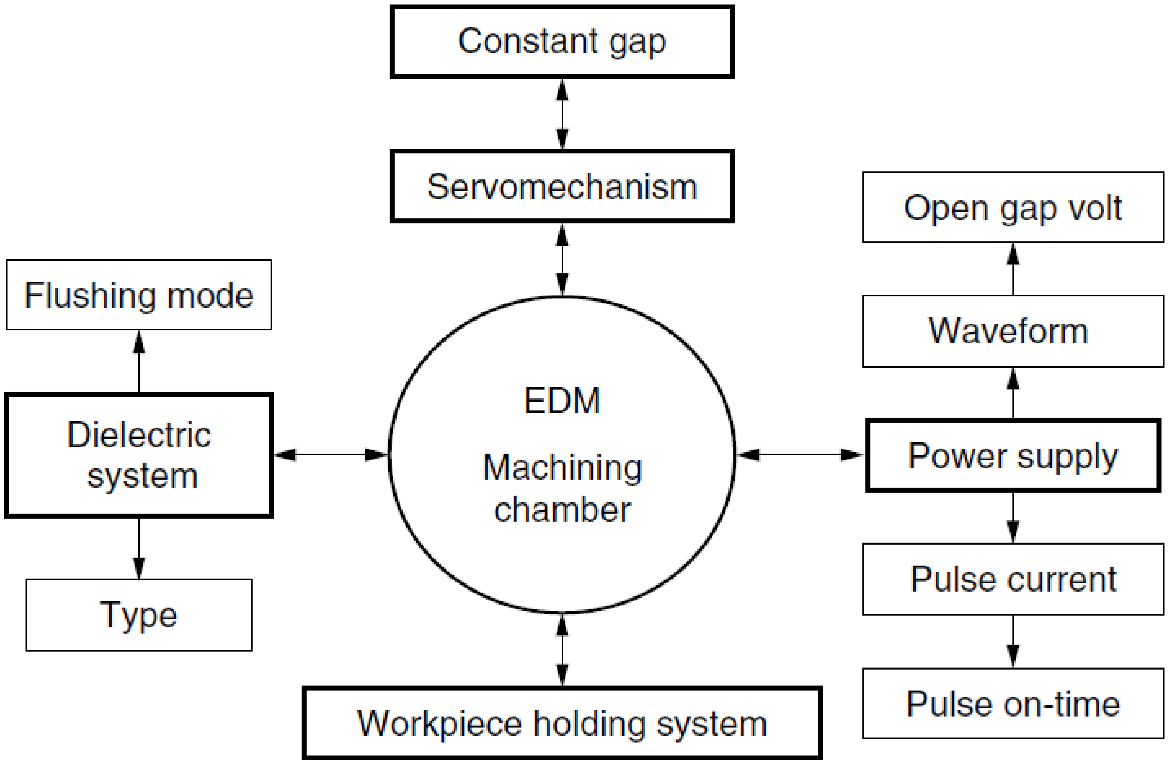
The EDM process involves a controlled erosion of electrically conductive materials by the initiation of rapid and spark discharge between the electrode tool (usually cathode) and workpiece (anode) separated by a small gap of about 0.01 – 0.50 mm known as the spark gap. The spark gap is either flooded or immersed under the dielectric fluid. The spark discharge is produced by the controlled pulsing of direct current, thus enabling a spark discharge to pass between the tool and the workpiece. Each spark produces enough heat to melt and vaporize a tiny volume of the workpiece material, leavening a small crater on its surface. The energy contained in each spark is discrete and it can be controlled so that the material removal rate, surface finish and tolerance can be predicted.

- Primarily used for hard metals or those that would be very difficult to machine with traditional techniques.
- EDM typically works with materials that are electrically conductive, although methods for machining insulating ceramics with EDM have been proposed.
- EDM can cut intricate contours or cavities in hardened steel without the need for heat treatment to soften and re-harden them.
- Also, applications of this process to shape polycrystalline diamond tools have been reported.
- MRR in EDM increases with Decrease in melting point of workpiece.

System



Components



- The main components in EDM:
    - Electric power supply
    - Dielectric medium
    - Work piece & tool
    - Servo control unit.
- The work piece and tool are electrically connected to a DC power supply.
- The current density in the **discharge** of the channel is of the order of **10000 A/cm^2** and **power density is nearly 500 MW/cm^2.**
- A gap, known as **SPARK GAP in the range, from 0.005 mm to 0.05 mm** is maintained between the work piece and the tool.
- Dielectric slurry is forced through this gap at a **pressure of 2 kgf/cm^2** or lesser.

Working Principle

- It is a process of metal removal based on the principle of material removal by an interrupted electric spark discharge between the electrode tool and the work piece.
- In EDM, a potential difference is applied between the tool and workpiece.

- Essential - Both tool and work material are to be conductors.
- The tool and work material are immersed in a dielectric medium.
- Generally, kerosene or deionized water is used as the dielectric medium.
- A gap is maintained between the tool and the workpiece.
- Depending upon the applied **potential difference (50 to 450 V)** and the gap between the tool and workpiece, an electric field would be established.
- Generally, the **tool is connected to the negative terminal (cathode)** of the generator and the **workpiece is connected to positive terminal (anode).**
- The high-speed electrons then impinge on the job and ions on the tool.
- The kinetic energy of the electrons and ions on impact with the surface of the job and tool respectively would be converted into thermal energy or heat flux.
- Such intense localized heat flux leads to extreme instantaneous confined rise in **temperature** which would be in excess of **10,000ºC.**
- Such localized extreme rise in temperature leads to material removal.
- **Material removal occurs due to instant vaporization of the material as well as due to melting.**
- The molten metal is not removed completely but only partially.

Electrode Material

- Electrode material should be such that it would not undergo much tool wear when it is impinged by positive ions.
- Thus, the localized temperature rise has to be less by properly choosing its properties or even when temperature increases, there would be less melting.
- Further, the tool should be easily workable as intricate shaped geometric features are machined in EDM.
- Thus, the basic characteristics of electrode materials are:
    - **High electrical conductivity** – electrons are cold emitted more easily and there is less bulk electrical heating
    - **High thermal conductivity** – for the same heat load, the local temperature rise would be less due to faster heat conducted to the bulk of the tool and thus less tool wear.
    - Higher density – for less tool wear and thus less dimensional loss or inaccuracy of tool
    - High melting point – high melting point leads to less tool wear due to less tool material melting for the same heat load
    - Easy manufacturability

    - Cost – cheap

- The followings are the different **electrode materials** which are used commonly in the industry:
    - Graphite
    - Electrolytic oxygen free copper
    - Tellurium copper – 99% Cu + 0.5% tellurium
    - Brass
- Graphite (most common) - has fair wear characteristics, easily machinable.
- Small flush holes can be drilled into graphite electrodes.
- Copper has good EDM wear and better conductivity.
- It is generally used for better finishes in the range of R_a = 0.5 µm.
- It has better electrical conductivity than graphite while the corner wear is higher.
- Brass ensures stable sparking conditions and is normally used for specialized applications such as drilling of small holes where the high electrode wear is acceptable.

Dielectric

- In EDM, material removal mainly occurs due to thermal evaporation and melting.
- As thermal processing is required to be carried out in absence of oxygen so that the process can be controlled and oxidation avoided.
- Oxidation often leads to poor surface conductivity (electrical) of the workpiece hindering further machining.
- Hence, dielectric fluid should provide an oxygen free machining environment.
- Further it should have enough strong dielectric resistance so that it does not breakdown electrically too easily.
- But at the same time, it should ionize when electrons collide with its molecule.
- Moreover, during sparking it should be thermally resistant as well.
- Generally, kerosene and deionized water is used as dielectric fluid in EDM.
- Tap water cannot be used as it ionizes too early and thus breakdown due to presence of salts as impurities occur.
- Dielectric medium is generally flushed around the spark zone.
- It is also applied through the tool to achieve efficient removal of molten material.
- Three important functions of a dielectric medium in EDM:

    - Insulates the gap between the tool and work, thus preventing a spark to form until the gap voltage are correct.
    - Cools the electrode, workpiece and solidifies the molten metal particles.
    - Flushes the metal particles out of the working gap to maintain ideal cutting conditions, increase metal removal rate.
- It must be filtered and circulated at constant pressure.
- The main requirements of the EDM dielectric fluids are adequate viscosity, high flash point, good oxidation stability, minimum odor, low cost, and good electrical discharge efficiency.
- For most EDM operations kerosene is used with certain additives that prevent gas bubbles and de-odoring.
- Other dielectric fluids with a varying degree of success include aqueous solutions of ethylene glycol, water in emulsions, and distilled water.

Material Removal Rate

- In EDM, the metal is removed from both workpiece and tool electrode.
- MRR depends not only on the workpiece material but on the material of the tool electrode and the machining variables such as pulse conditions, electrode polarity, and the machining medium.
- In this regard a material of low melting point has a high metal removal rate and hence a rougher surface.
- Typical removal rates range from 0.1 to 400 mm^3 /min.
- MRR or volumetric removal rate (VRR), in mm^3/min, was described by Kalpakjian (1997):

Mechanism of material removal

- Potential difference
- Generally tool(-ve), Work piece(+ve)
- Electric field is established
- Tool and work piece conductor of electricity
- Free electrons are available
- If work function is low, electron get emitted from tool
- Cold emission of electron and acceleration of same
- Collision of electron with dielectric molecules-more ions & electron
- "Avalanche motion" of electrons-spark(Erosion)
- Impingement of work piece by high energy electron
- High temperature on work piece-localised melting
- Shock wave-material removal

Name of Discipline

$$\text{VRR} = (4 \times 10^4) i T_w^{-1.23}$$

where I - EDM current (A)

T_w - Melting point of the workpiece (°C).

Characteristics

- Can be used to machine any work material if it is electrically conductive.
- MRR depends on thermal properties (job) rather than its strength, hardness etc.
- The volume of the material removed per spark discharge is typically in the range of (1/1,000,000) to (1/10,000) mm^3.
- Tool wear once again depends on the thermal properties of tool material.
- Local temperature rise is rather high, but there is not enough heat diffusion (very small pulse on time) and thus HAZ is limited to 2 – 4 µm.
- Rapid heating and cooling leads to surface hardening which may be desirable in some applications.
- Tolerance value of $\pm$ 0.05 mm could be easily achieved by EDM.

- Best surface finish that can be economically achieved on steel is 0.40 μm.

Applications

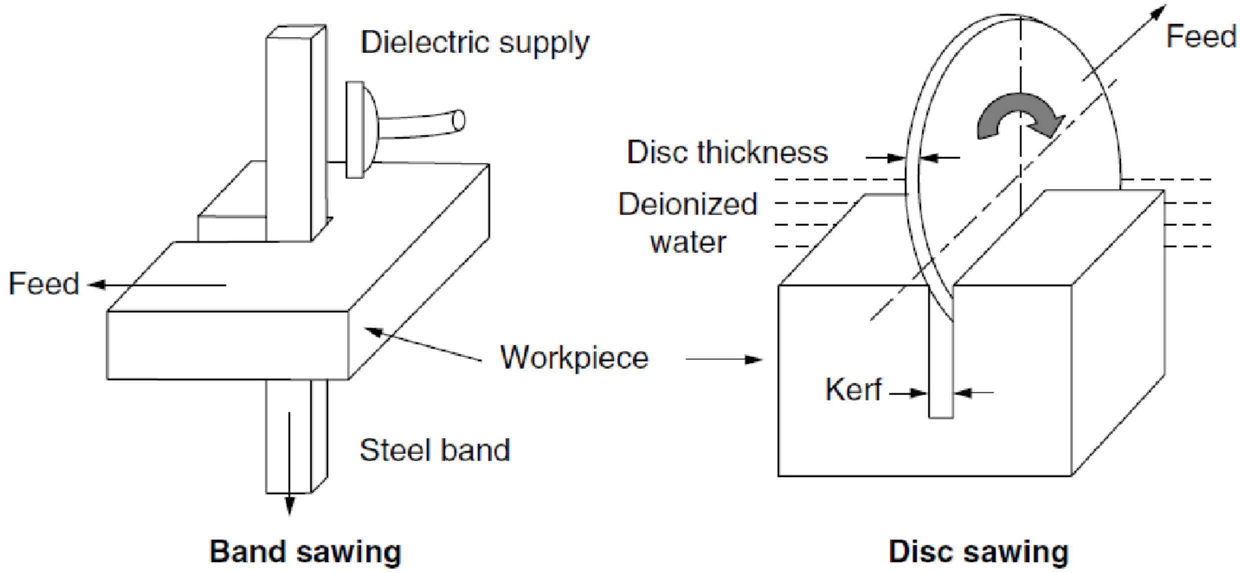
- Drilling of micro-holes, thread cutting, helical profile milling, rotary forming, and curved hole drilling.
- Delicate work piece like copper parts can be produced by EDM.
- Can be applied to all electrically conducting metals and alloys irrespective of their melting points, hardness, toughness, or brittleness.
- Other applications: deep, small-dia holes using tungsten wire as tool, narrow slots, cooling holes in super alloy turbine blades, and various intricate shapes.
- EDM can be economically employed for extremely hardened work piece.
- Since there is no mechanical stress present (no physical contact), fragile and slender work places can be machined without distortion.
- Hard and corrosion resistant surfaces, essentially needed for die making, can be developed.

Applications - EDM Drilling

- Uses a tubular tool electrode where the dielectric is flushed.
- When solid rods are used; dielectric is fed to the machining zone by either suction or injection through pre-drilled holes.
- Irregular, tapered, curved, as well as inclined holes can be produced by EDM.
- Creating cooling channels in turbine blades made of hard alloys is a typical application of EDM drilling.
- Use of NC system enabled large numbers of holes to be accurately located.

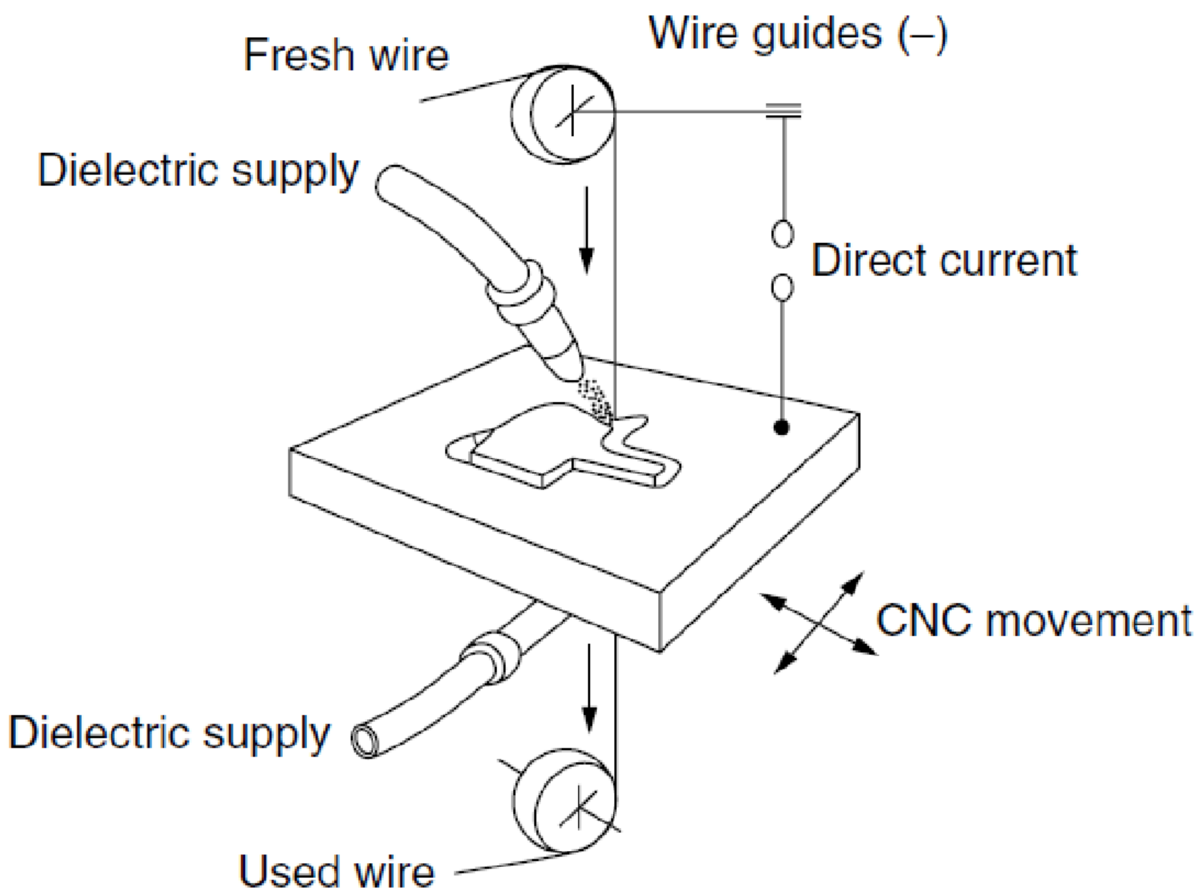
Applications – EDM Sawing

- An EDM variation - Employs either a special steel band or disc.
- Cuts at a rate that is twice that of the conventional abrasive sawing method.
- Cutting of billets and bars - has a smaller kerf & free from burrs.
- Fine finish of 6.3 to 10 µm with a recast layer of 0.025 to 0.130 mm



Applications – Wire EDM

- Special form of EDM - uses a continuously moving conductive wire electrode.
- Material removal occurs as a result of spark erosion as the wire electrode is fed, from a fresh wire spool, through the workpiece.
- Horizontal movement of the worktable (CNC) determines the path of the cut.
- Application - Machining of super hard materials like polycrystalline diamond (PCD) and cubic boron nitride (CBN) blanks, and other composites.
- Carbon fiber composites are widely used in aerospace, nuclear, automobile, and chemical industries, but their conventional machining is difficult.



Advantages

Some of the advantages of EDM include machining of:

- Complex shapes that would otherwise be difficult to produce with conventional cutting tools.
- Extremely hard material to very close tolerances.
- Very small work pieces where conventional cutting tools may damage the part from excess cutting tool pressure.
- There is no direct contact between tool and work piece. Therefore, delicate sections and weak materials can be machined without any distortion.
- A good surface finish can be obtained.

Disadvantages

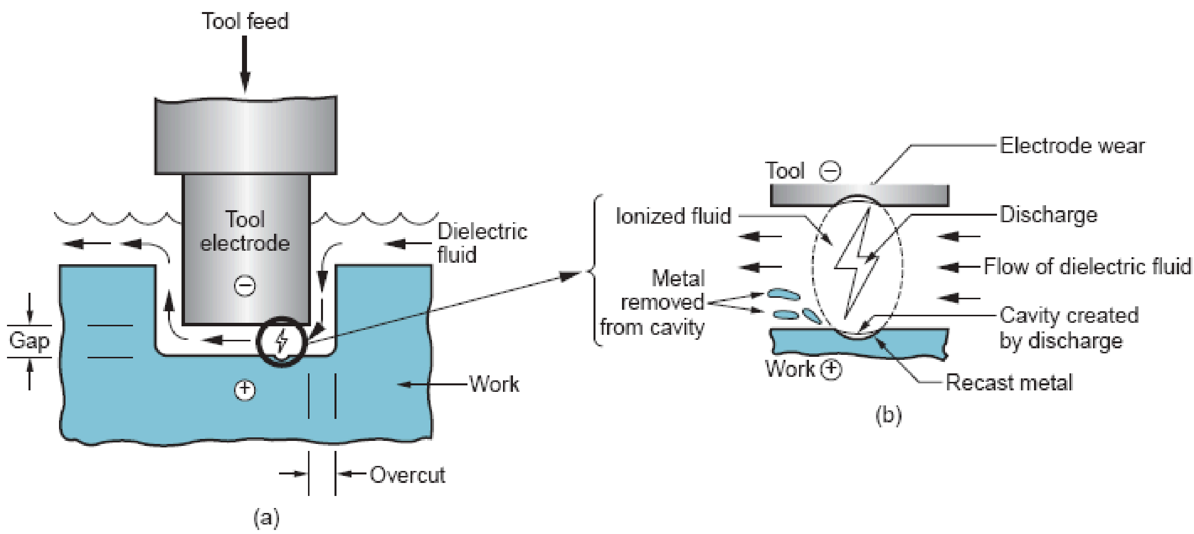
Some of the disadvantages of EDM include:

- The slow rate of material removal.
- For economic production, the surface finish specified should not be too fine.

- Reproducing sharp corners on the workpiece is difficult due to electrode wear.
- Specific power consumption is very high.
- Excessive tool wear occurs during machining.
- Electrically non-conductive materials can be machined only with specific set-up of the process

Process Parameters

Metal removal rate – MRR is proportional to the working current value. It is generally described



Laser Beam Machining

- Laser Beam Machining is carried out utilizing the energy of coherent photons or laser beam, which is mostly converted into thermal energy upon interaction with most of the materials.
- Laser Beam Machining or more broadly laser material processing deals with machining and material processing like heat treatment, alloying, cladding etc.
- Laser stands for " Light Amplification by Stimulated Emission of Radiation".
- Laser beam can very easily be focused using optical lenses as their **wavelength ranges from half micron to around 70 microns**. Focused laser beam as indicated earlier can have **power density** in excess of **1 MW/mm^2**.

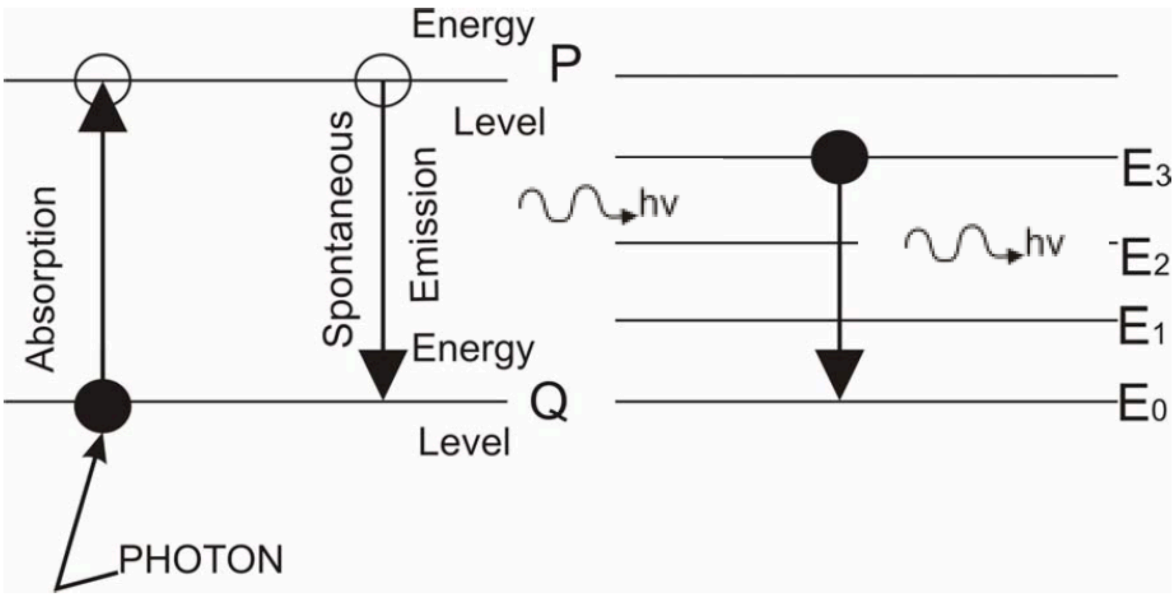
Laser Properties

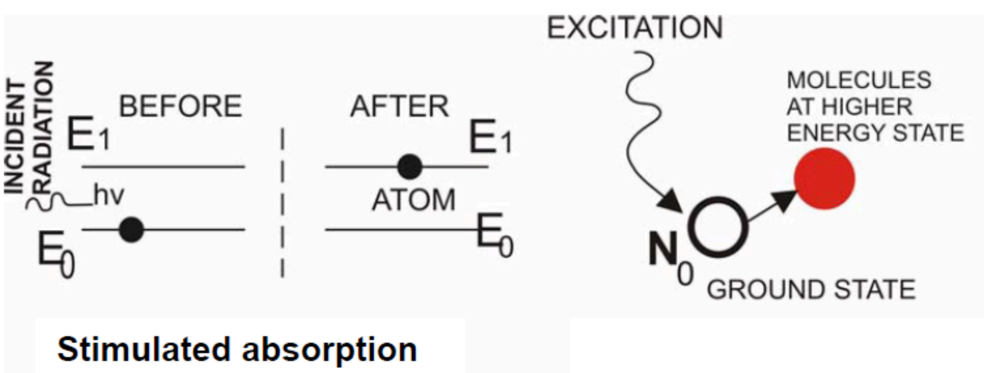
- **Laser has certain unique properties, namely, high monochromaticity, coherence and directionality, compared to ordinary sources of light, though both are electromagnetic radiations.**
- **Monochromaticity:** In an ideal case, the laser emits all photons with the same energy, and thus the same wavelength, it is said to be monochromatic.

- **Coherence:** The two emitted photons are said to be in phase, which means that the crest or the trough of the wave associated with one photon will occur at the same time as on the wave associated with the other photon.

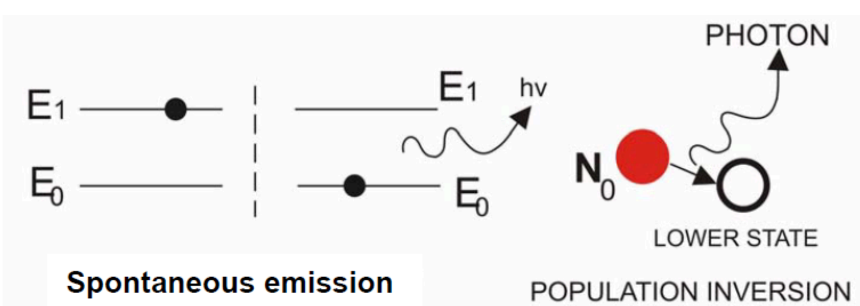
The Lasing Process

- Lasing process describes the basic operation of laser, i.e. generation of coherent beam of light by "light amplification" using "stimulated emission".

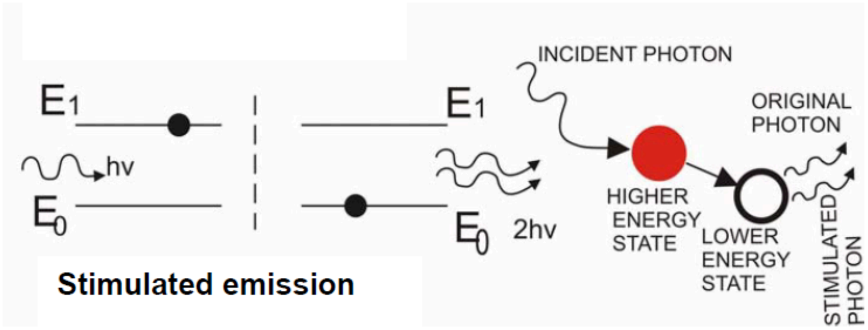


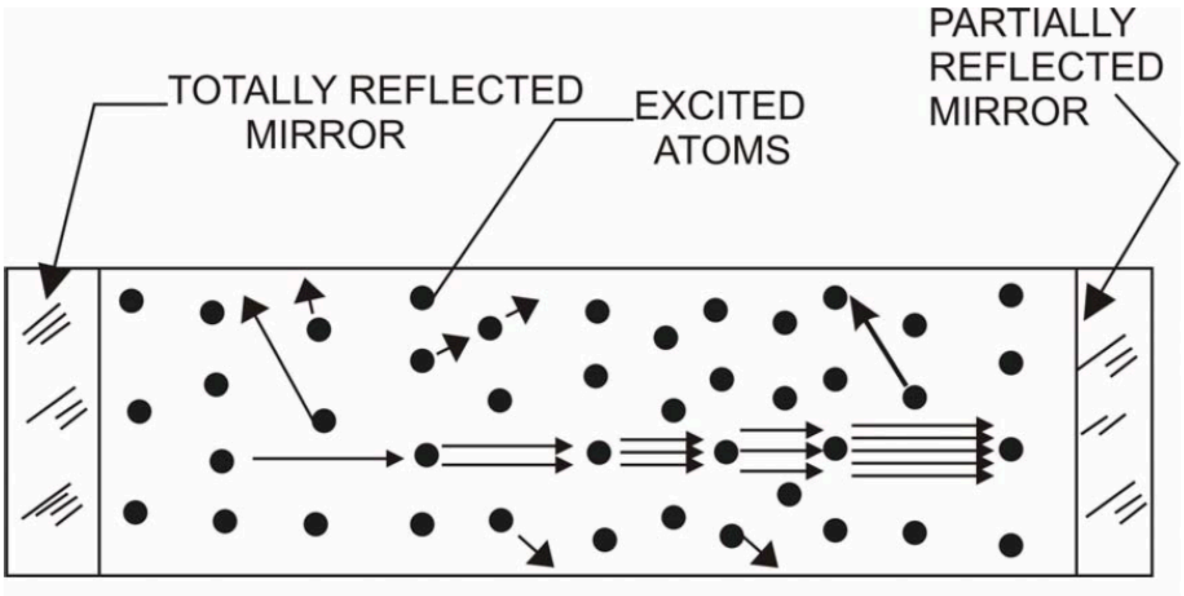


Stimulated absorption



Spontaneous emission





Lasing Medium

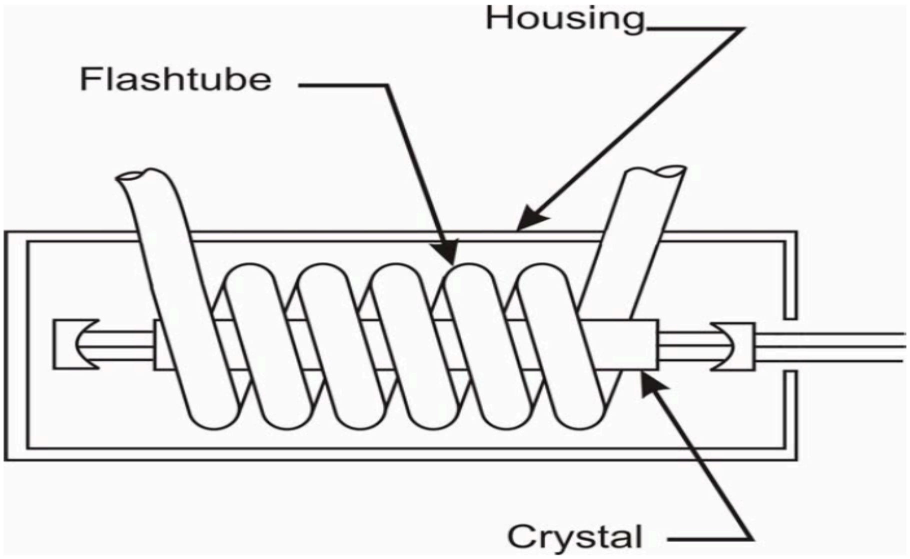
- Depending on the lasing medium lasers are classified as solid state and gas laser.
- Solid-state lasers are commonly of the following type

1. Ruby which is a chromium – alumina alloy having a wavelength of 0.7 µm
2. Nd-glass lasers having a wavelength of 1.64 µm
3. Nd-YAG laser having a wavelength of 1.06 µm

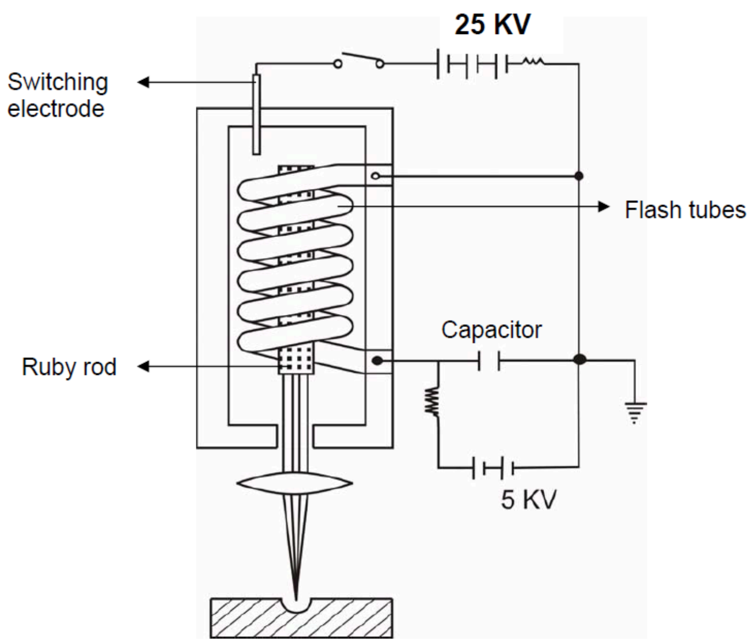
- The generally used gas lasers are

1. Helium – Neon
2. Argon
3. CO^2 etc.

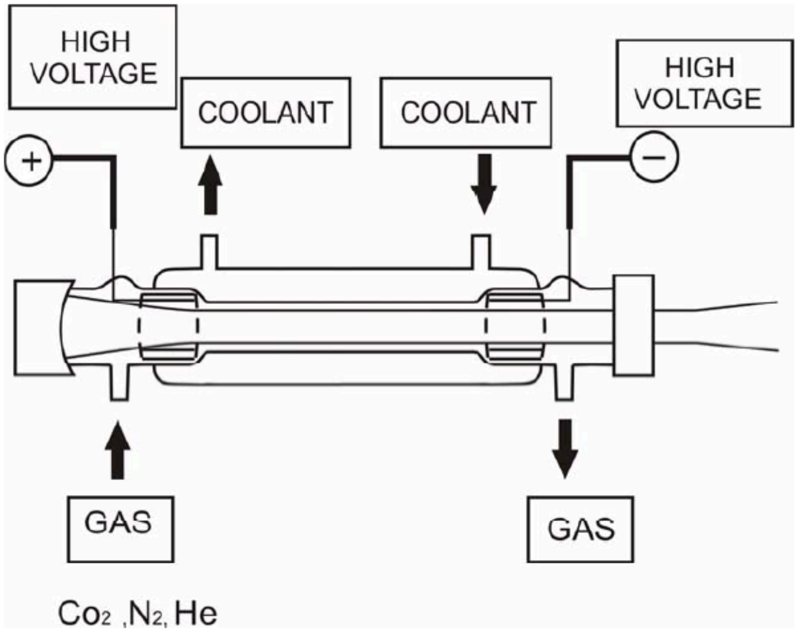
Laser Construction



Electrical circuit for operation of a solid – state laser



Construction of a CO_2 laser



Application

- Laser can be used in wide range of manufacturing applications

1. Material removal – drilling, cutting and tre-panning
2. Welding
3. Cladding
4. Alloying

- Drilling micro-sized holes using laser in difficult – to – machine materials is the most dominant application in industry. In laser drilling the laser beam is focused over the desired spot size. For thin sheets pulse laser can be used. For thicker one's continuous laser may be used.

Advantages

- In laser machining there is no physical tool. Thus, no machining force or wear of the tool takes place.
- Large aspect ratio in laser drilling can be achieved along with acceptable accuracy or dimension, form or location
- Micro-holes can be drilled in difficult – to – machine materials
- Though laser processing is a thermal processing but heat affected zone specially in pulse laser processing is not very significant due to shorter pulse duration.

Limitations

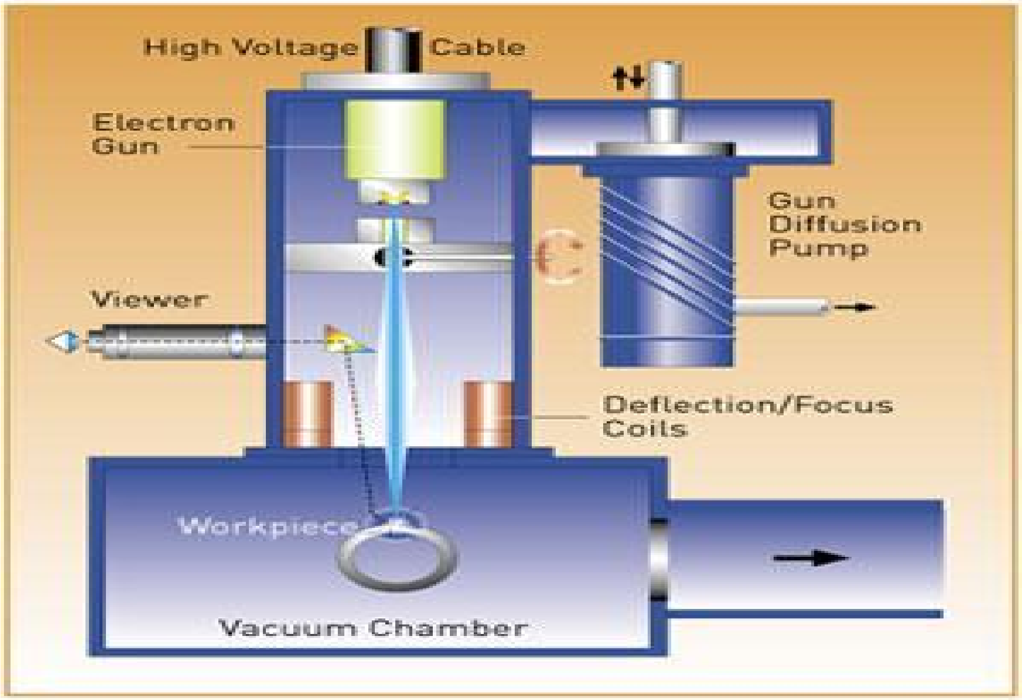
- High initial capital cost

- High maintenance cost
- Presence of Heat Affected Zone – specially in gas assist CO_2 laser cutting
- Thermal process – not suitable for heat sensitive materials like aluminum glass fiber laminate

Electron Beam Machining - Thermal and Non-Thermal

- **Electron-beam machining (EBM) is a process where high-velocity electrons concentrated into a narrow beam are directed toward the work piece, creating heat and vaporizing the material**.
- **EBM can be used for very accurate cutting or boring of a wide variety of metals.**
- Electrical energy is used to generate high-energy electrons in case of Electron Beam Machining (EBM). The EBM beam is operated in pulse mode
- Use of electron beam
- Machining of metals by bombarding a specific confined area of base metal with high velocity electrons
- **The electrons strike the work piece and their kinetic energy converts into thermal energy heating the metal**
- The edges of work piece are melted and vaporize
- Process performed in vacuum chamber
- **Pressure (0.00013 to 0.0013 Pa)**
- If no vacuum, electrons would strike the small particles in atmosphere, reducing their velocity and heating ability

- Electron gun
- Cathode - tungsten filament at 2500 – 3000 degC



Working

- The electrons are emitted by a heated tungsten filament or cathode (electron gun).
- Electrons accelerated by huge potential voltage b/w cathode and anode (speed 30000-120000 miles/sec)
- High voltage (about 150 kV) applied between the cathode and the anode; the electrons are accelerated up to 30% - 60% of the speed of light.
- Electrons travels through a series of focusing lenses
- Then focused into a thin beam in the focusing coil. Deflection coil moves the electron beam along the machining area
- When beam strikes the machining point Kinetic energy of high-speed electrons converted into heat
- This heat becomes sufficient for melting the targeted area.
- Greater the KE, large amount of heat released
- The temp is so higher that even ceramic materials can cut or welded

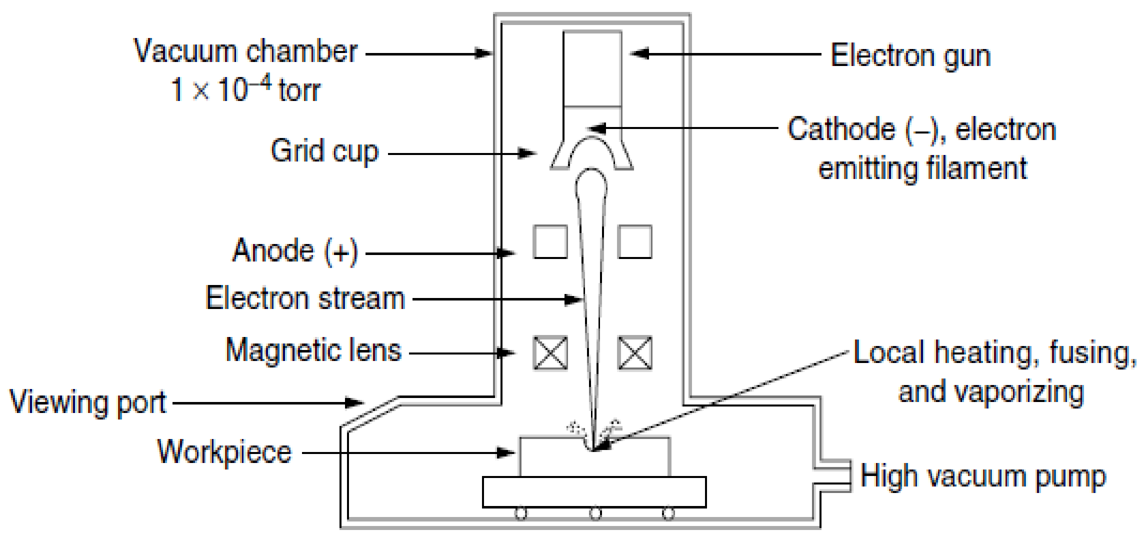
System

- The EB system is composed of an electron beam gun, a power supply, control system, motion equipment and vacuum welding chamber.
- The vacuum requirement for operation of the electron beam

- The electron beam stream and workpiece are manipulated by means of precise, computer driven controls, within a vacuum chamber

Components

- Electron Gun
- Vacuum Chamber and Vacuum pump system
- Work holding table (movable)
- An electronic system
- A monitoring system



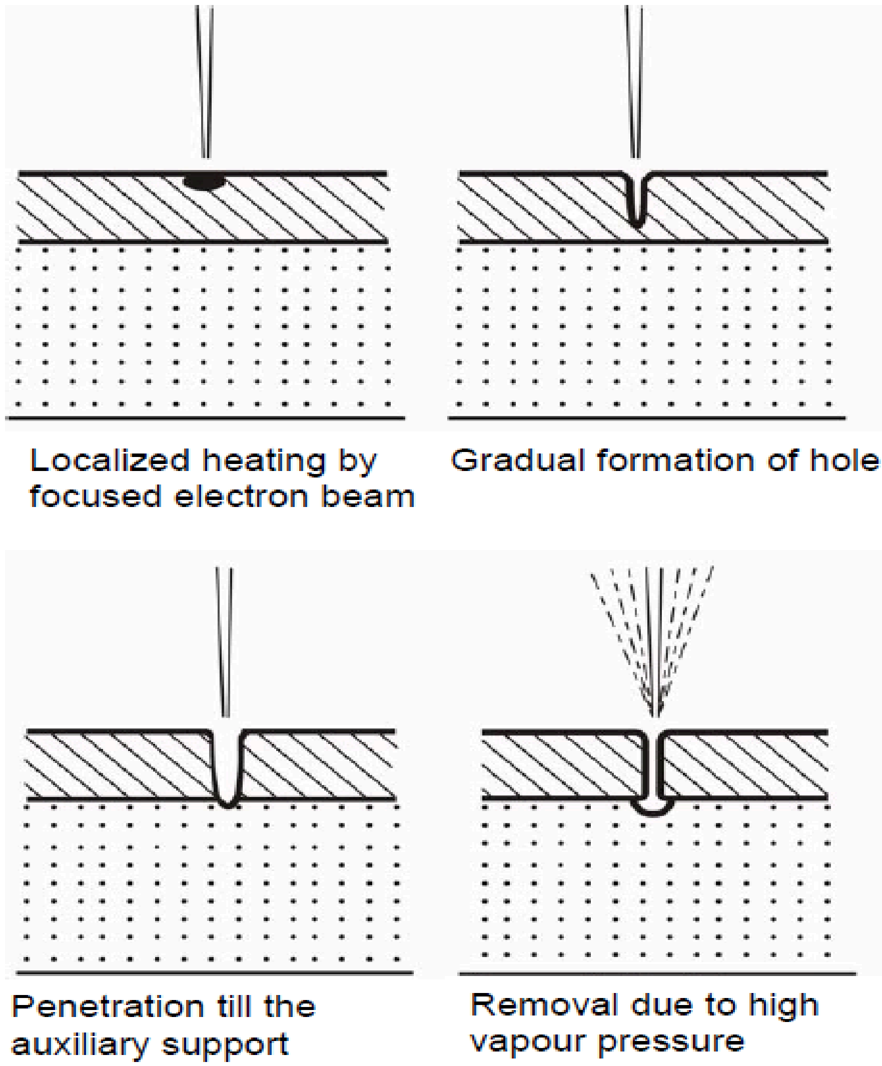
Components of an EBM system.

Process

- Electron beam is generated in an electron beam gun.
- Electron beam gun provides high velocity electrons over a very small spot size.
- Electron Beam Machining is required to be carried out in vacuum.
- The high-energy focused electron beam is made to impinge on the work piece with a spot size of 10 – 100 μm.
- The kinetic energy of the high velocity electrons is converted to heat energy as the electrons strike the work material. Due to high power density instant melting and vaporization starts.

- Finally, the molten material is expelled from the cutting zone by the high vapour pressure at the lower part.

Mechanism of Material Removal



Electron Beam Gun

- The basic functions of any electron beam gun are to generate free electrons at the cathode, accelerate them to a sufficiently high velocity and to focus them over a small spot size.
- The cathode is generally made of tungsten or tantalum and given a high negative bias.
- Just after the cathode, there is an annular bias grid.
- The next element is the annular anode. The annular anode attracts the electron beam and gradually gets accelerated.

- The biased grid is used as a switch to operate the electron beam gun in pulsed mode.
- The magnetic lenses shape the beam and try to reduce the divergence.
- Apertures on the other hand allow only the convergent electrons to pass and capture the divergent low energy electrons
- Then the electron beam passes through the final section of the electromagnetic lens and deflection coil.
- The electromagnetic lens focuses the electron beam to a desired spot.
- The deflection coil can guide the electron beam, though by small amount, to improve shape of the machined holes.
- Generally, in between the electron beam gun and the work piece, which is also under vacuum, there would be a series of slotted rotating discs.
- Such discs allow the electron beam to pass and machine materials but helpfully prevent metal fumes and vapour generated during machining to reach the gun.
- Thus, it is essential to synchronize the motion of the rotating disc and pulsing of the electron beam gun.
- Electron beam guns are also provided with illumination facility and a telescope for alignment of the beam with the work piece.
- Work piece is mounted on a CNC table so that holes of any shape can be machined using the CNC control and beam deflection in-built in the gun.
- One of the major requirements of EBM operation of electron beam gun is maintenance of desired vacuum. Level of vacuum within the gun is in the order of 10^{-4} to 10^{-6} Torr.
- Such vacuum is achieved and maintained using a combination of rotary pump and diffusion pump.
- Diffusion pump is attached to the diffusion pump port of the electron beam gun.

Process Parameters

- The accelerating voltage
- The beam currents
- Pulse duration
- Energy per pulse
- Power per pulse
- Spot size
- Power density

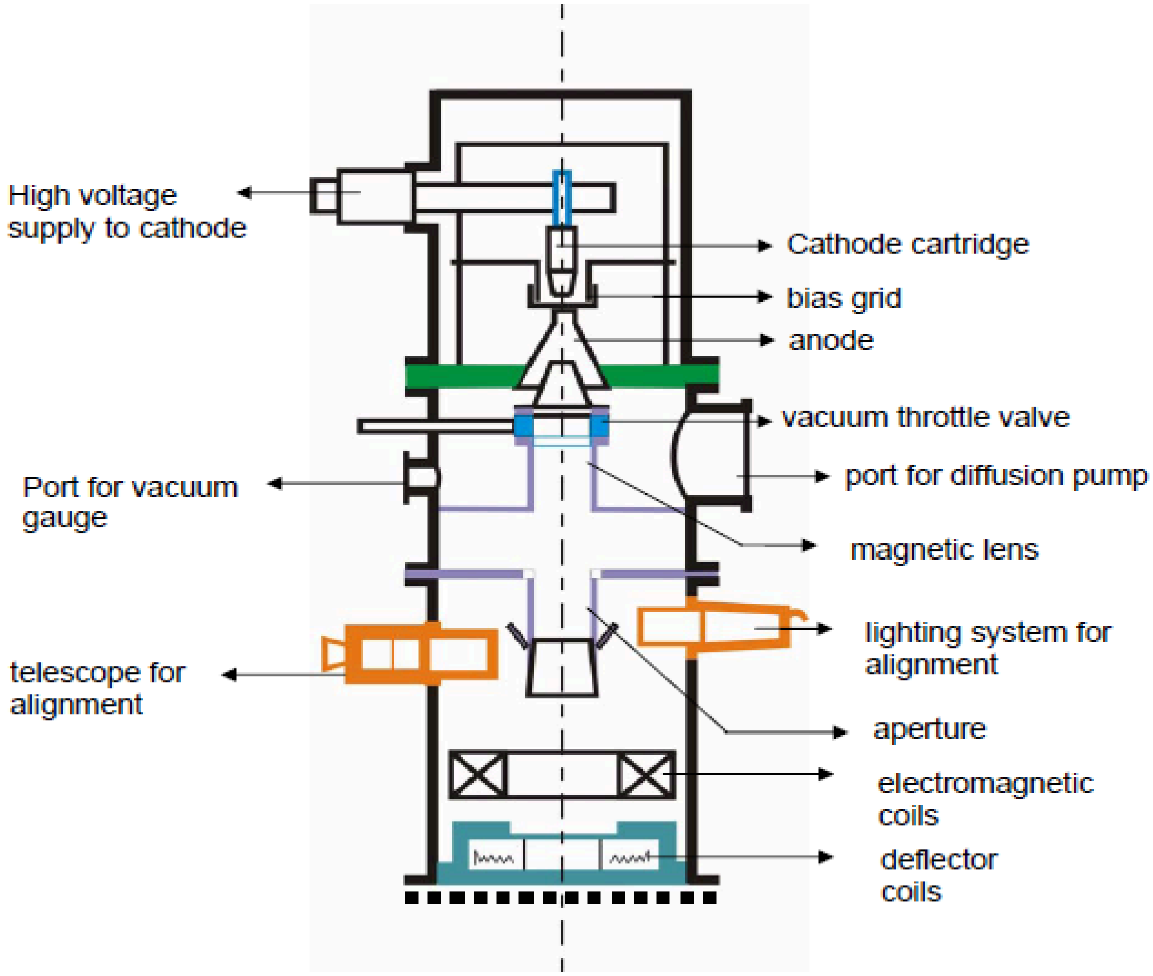
- Switching pulses are given to the bias grid so as to achieve pulse duration of as low as 50 μs to as long as 15 ms.
- Beam current is directly related to the number of electrons emitted by the cathode or available in the beam. Beam current once again can be as low as 200 μamp to 1 amp.
- Increasing the beam current directly increases the energy per pulse. Similarly increase in pulse duration also enhances energy per pulse. High-energy pulses (in excess of 100 J/pulse) can machine larger holes on thicker plates.
- Spot size is controlled by the degree of focusing achieved by the electromagnetic lenses. A higher energy density, i.e., for a lower spot size, the material removal would be faster though the size of the hole would be smaller.

Capability

- **EBM can provide holes of diameter in the range of 100 μm to 2 mm with a depth upto 15 mm, i.e., with a l/d ratio of around 10.**
- **A wide range of materials such as steel, stainless steel, Ti and Ni super-alloys, aluminum as well as plastics, ceramics, leathers can be machined successfully using electron beam.**
- EBM does not apply any cutting force on the workpieces. Thus, very simple work holding is required. This enables machining of fragile and brittle materials by EBM.

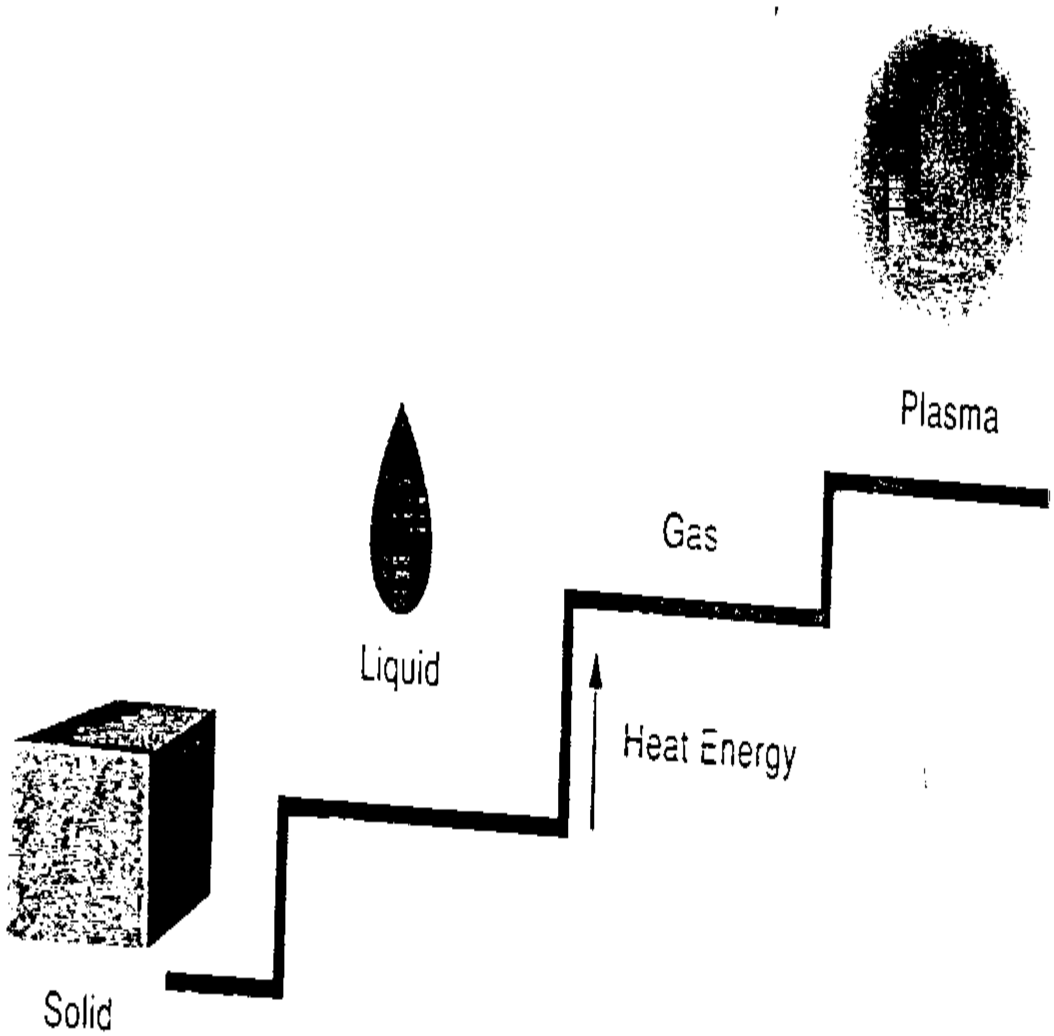
Advantages and Limitations

- EBM provides very high drilling rates when small holes with large aspect ratio are to be drilled.
- It can machine almost any material irrespective of their mechanical properties.
- As it applies no mechanical cutting force, work holding and fixturing cost is very less. Further for the same reason fragile and brittle materials can also be processed.
- The heat affected zone in EBM is rather less due to shorter pulses.
- EBM can provide holes of any shape by combining beam deflection using electromagnetic coils and the CNC table with high accuracy.
- The primary limitations are the high capital cost of the equipment and necessary regular maintenance applicable for any equipment using vacuum system.
- Moreover, in EBM there is significant amount of non-productive pump down period for attaining desired vacuum.



Electron Beam Gun

Plasma machining



Machines

- Most, if not all, of the light portable plasma cutters are 110-volt machines.
  - Suited primarily for cutting sheet metal and other light work.
- The next level up is the 220-volt machines with 50 to 80-amp output current.
  - These are portable from the standpoint that one person can put it on a truck and take it to the job.

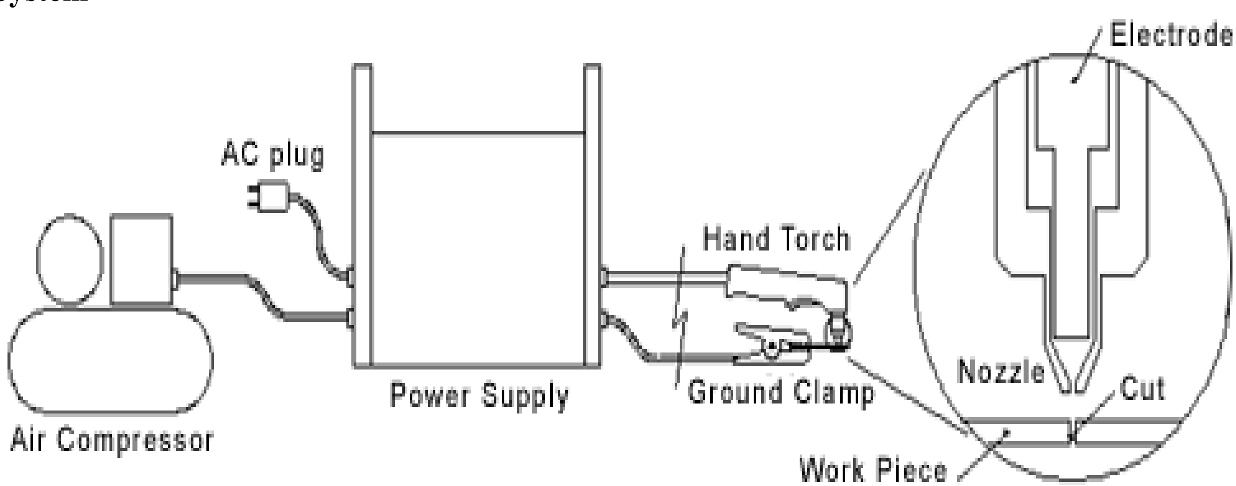
How a Plasma Cutter works

- A complete plasma cutter consists of a
  - power supply,

- a ground clamp,
- and a hand torch.

- The main function of the power supply is to convert the AC line voltage into a user-adjustable regulated (continuous) DC current.
- The hand torch contains a trigger for controlling the cutting, and a nozzle through which the compressed air blows. An electrode is also mounted inside the hand torch, behind the nozzle.

System

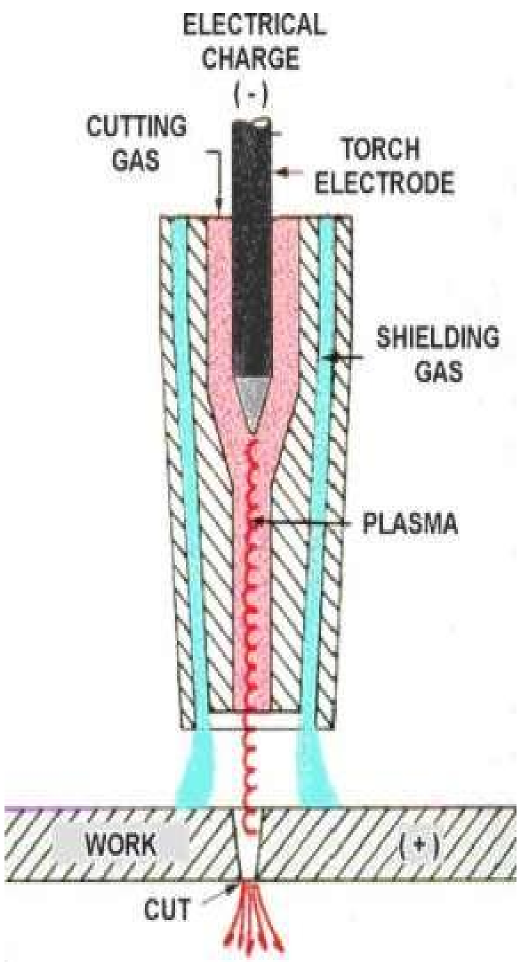


Operation

- Initially, the electrode is in contact with (touches) the nozzle.

- When the trigger is squeezed, DC current flows through this contact.
- Next, compressed air starts trying to force its way through the joint and out the nozzle.
- Air moves the electrode back and establishes a fixed gap between it and the tip.
    - The power supply automatically increases the voltage in order to maintain a constant current through the joint - a current that is now going through the air gap and turning the air into plasma.
- Finally, the regulated DC current is switched so that it no longer flows through the nozzle but instead flows between the electrode and the work piece. This current and airflow continues until cutting is halted.

PAM



Common torch parts

Parts of the torch

Electrode

Tip nozzle insulator

Nozzle tip

Nozzle guide

Nozzles and the metal parts are usually made out of copper, and they may be plated.

The plating of copper parts will help stay spatter-free longer.

Electrode Tip

- Electrode tip is often made of copper electrode with a tungsten tip attached.
- Use of copper/tungsten tip has improved the quality of work they can produce.
- By using copper, the heat generated at the tip can be conducted away faster.
- Keeping the tip as cool as possible lengthens the life of the tip and allows for better quality cuts for a longer time.
- Old torches you must grind the tungsten electrode

Cutting Speeds

- High cutting speeds are possible
  - Up to 300 inches per minute

– 25 feet a minute

– ¼ mile an hour

Characteristics of Plasma Arc machining

The characteristics of PAM are summarized as follows:

1. In plasma arc machining, the cutting rates obtained are 2500 to 1700 mm / min and it depends upon the type of work material to be used and its thickness.
2. The planes that are machined by using plasma torch are smoother than the planes machined by oxy-acetylene flame.
3. However, the ends of the surfaces are rounded in the shape.
4. The walls of the cut have a v-shape which has an inclination of 5 to 10 degrees. The nozzle having more than one port operating under perfect condition will decrease this angle to 20 degrees. It has kerf width which varies from 2.5 to 9 mm.
5. The accuracy of width of slots and diameter of holes vary for different thickness of plates, such as 0.8 mm for 6 to 30 mm + 0.3 mm for 100 to 150 mm thick plates.

In PAM, the deepness Of heat affected zone is generally depends upon the following:

(i) Material of the work piece

(ii) Thickness of work piece

(iii) Cutting speed.

Merits and De-Merits

Merits-

1. The main advantage of PAM is that it uniformly effects the material irrespective of its hardness or refractory nature since there is no connection between the tool and work piece.
2. The cutting rates in this method are high enough to assist the PAM technique on all the materials.

De-merits-

1. Surfaces contain metallurgical alterations,
2. It requires secondary machining on the surfaces.
3. Operators require eye shielding and noise protection.

Uses of Plasma in Manufacturing Industries

The uses of plasma in the various fields of manufacturing industries are as follows:

1. The most important application of plasma arc machining is the profile cutting of metals, specifically steel and aluminum.
2. By using plasma arc machining, the profile cutting of metals such as mild steel alloy steel and titanium can be done instantaneously and clearly.
3. Plasma arc machining increases the rate of production in various manufacturing industries by incorporating the computer numerical control table.
4. Plasma Arc Machining is employed for rough turning of medium size bar stocks. It is also used for turning of hardened shafts so that it can be utilized for making grooves on various pulleys.
5. In normal turning and milling machines, plasma is used for machining of hard materials.
6. Plasma arc machining involves some other applications such as:

A. Plasma arc surfacing, used for facing of hard alloys

B. It is used for generating surface coating of refractory materials. It is also used for the fabrication of free standing shapes.

Safety precautions

The safety precautions that are to be taken while performing plasma arc machining are as follows:

1. It is essential to protect the eyes from the ultraviolet and infrared radiations. These radiations are generated from the plasma flame and served in large quantity, it will be harmful to the eye. Hence, more care must be taken while working with plasma.
2. The over-ex in of ultraviolet and infrared radiation causes the reddening and due to loss of sleep a gritty feeling will be observed by an operator.
3. The overexposing of ultraviolet rays may lead to painful skin burns and cancer in most of the cases.
4. It is very essential that before going near to the torch, the worker should wear proper glasses and dresses.
5. The worker should cover the most of the body and quality of glasses must be good, so that it can protect from ultraviolet and infrared rays.
6. The torches are required to be operated in an airy room so that toxic gases such as NO, O2 etc., can be synthesized in the atmosphere.
7. While operating the torch, it may be noticed that the noise levels are very high. Hence, ear plugs should be used to protect the ears.
8. While operating the hand torches, the worker should wear asbestos gloves having leather as inner layer.

9. Every operator seek a consultation by a health physician depending upon the hours limit in operating the plasma torch.

Thermal Spraying Processes-Combustion (Detonation gun process) and electrical (plasma spraying)

- Thermal spraying, also commonly known as metal spraying is a surface engineering / coating process where a wide range of metals and non-metals can be sprayed onto the surface of another material**.**
- The coating material (metallic / non-metallic) in the form of powder, wire or rod is melted by an energy source (flame, electric arc, plasma arc) to a molten or semi molten state and is after that accelerated and propelled towards the substrate by gas / atomization jet.
- Thermal spraying is widely used to provide corrosion protection to ferrous metals or to change the surface properties such as the wear resistance, thermal insulation, electrical insulation/conduction, radiation protection and restoration of worn parts etc .

Working Principle

- All thermal spraying processes rely on the principle of

1. Heating a feed stock material (powder or wire).
2. Accelerating it to a high velocity.
3. Allowing the particles to strike the substrate surface.
4. The particles will then deform and freeze onto the substrate.

- The coating is formed when millions of particles are deposited on top of each other.

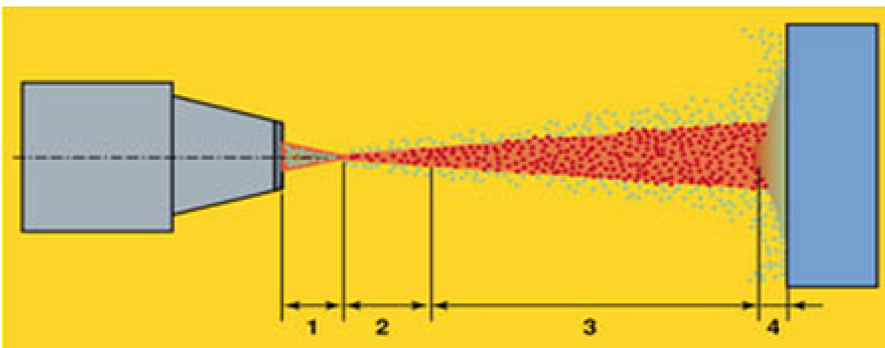
Process

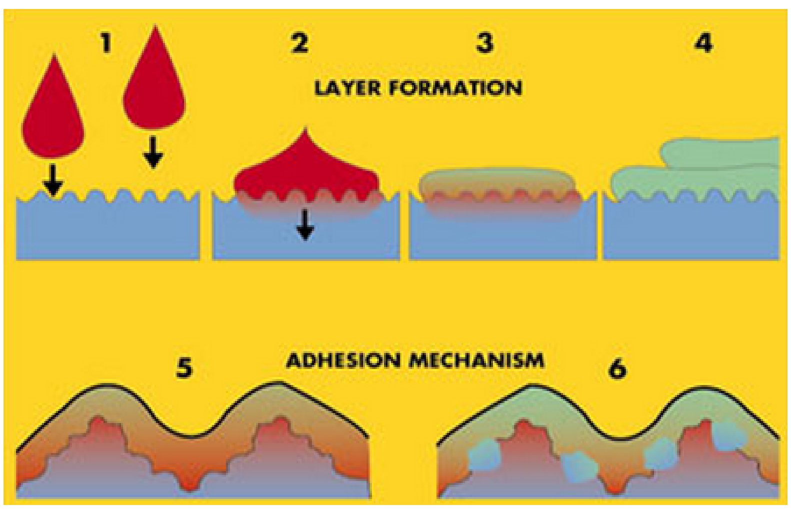
- Substrate preparation: Cleaning: removal of contaminants, such as oil, rust, etc.
- Surface preparation: Roughening: providing bigger possibility for the sprayed material to form bonds and/or be mechanically interlocked with the surface
- Preparation of sprayed material: to eliminate moisture, in order to avoid the coalescence of powder during spraying and to avoid degradation of coating's properties through hydroxides' formation.
- Heating of the surface: moisture removal, pre-expansion of the substrate

Steps of Spraying

- Fusion
- Atomization and speed control
- Temperature and speed control

- Coating building
- Transport of spraying particles
- Impact on the surface
- Thermal transfer from particles to substrate
- Solidification and contraction of particles
- Mechanical bond
- Local fusion





- Thermal spray processes may be categorized as either combustion or electric processes.

1. **Electric processes**

• Arc spraying

• Plasma spraying

2. **Combustion processes**

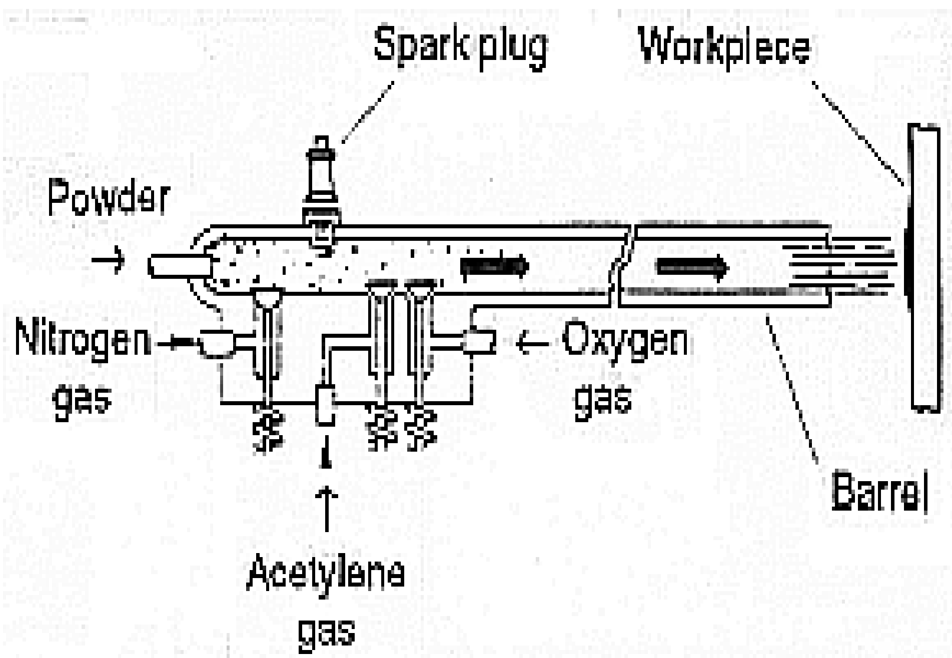
• Flame spraying

• High-velocity oxygen fuel spraying (HVOF)

• Detonation gun spraying (D-Gun)

Detonation Spray Process

- Detonation gun (D-gun) process is considered the first high velocity thermal spray process.
- Water cooled gun barrel
- Oxygen and fuel gas (generally Acetylene) mixture
- Coating material in form of powder
- Ignition by spark plug
- Detonation



- Depending upon the ratio of the combustion gases, the temperature of the hot gas stream can go up to *3890°C* and the velocity of the shock wave can reach 3500m/s.
- The coating thickness developed on the work piece per shot depends on the ratio of combustion gases, powder particle size, carrier gas flow rate, frequency and distance between the barrel end and the substrate.

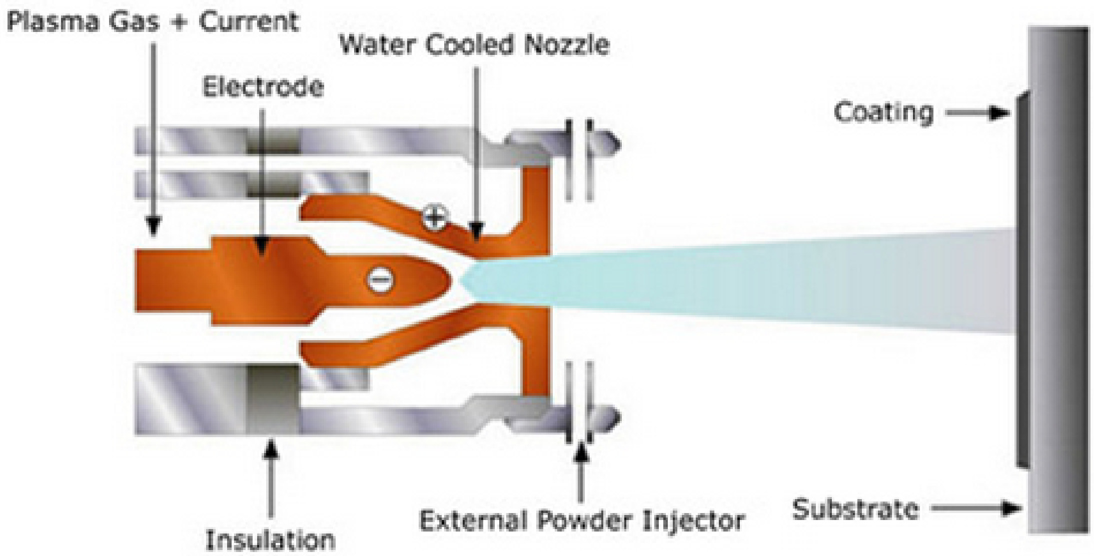
Advantages and Limitations

- Low substrate temperature
- High bond strength
- Dense Coatings

- Less scrap
- High level of noise (> 140 dB)
- Need for sealed boxes

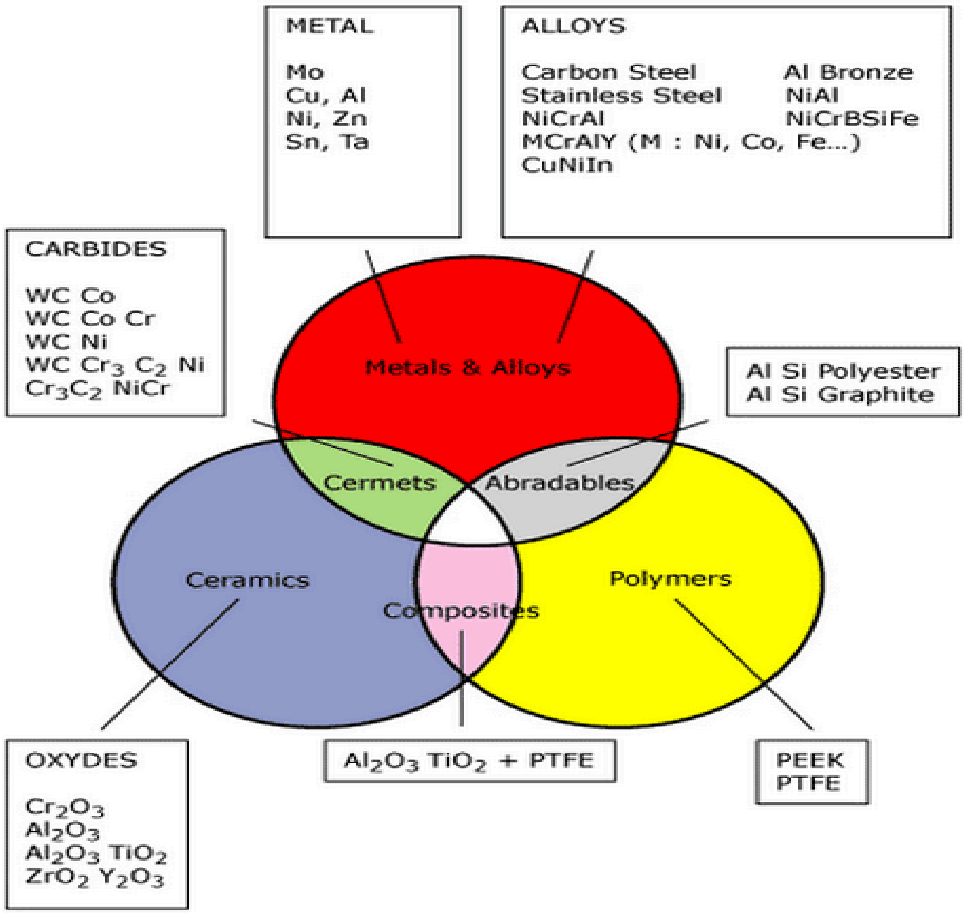
Plasma Spray Process

- Plasma Spray process uses a DC electric arc to generate a stream of high temperature ionized plasma gas, which acts as the spraying heat source.
- Powder is carried in inert gas into plasma jet.
- Temperature of the range of 15000 C can be achieved.



- Plasma spraying produces a high quality coating by the combination of a high temperature, high energy heat source, a relatively inert spraying medium and quite high particle velocities, typically 200-300 m/s.
- Plasma spraying has the advantage that it can spray very high melting point materials such as refractory metals like tungsten and ceramics like zirconium.

Feed Stock Material (Coating Material)



Rapid Prototyping

The term *rapid prototyping* (RP) refers to a class of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data.

These "three dimensional printers" allow designers to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures.

- Of course, "rapid" is a relative term.
  - Most prototypes require from three to seventy-two hours to build, depending on the size and complexity of the object.
  - This may seem slow, but it is much faster than the weeks or months required to make a prototype by traditional means such as machining.

- These dramatic time savings allow manufacturers to bring products to market faster and more cheaply.

- Such models have numerous uses:
  - Excellent visual aids for communicating
  - Prototypes can be used for design testing.
  - Used to make tooling
  - Used to make production-quality parts

Rapid Prototyping techniques

All Rapid Prototyping techniques employ the same basic five-step process.

1. Create a CAD model of the design
2. Convert the CAD model to STL format (stereolithography)
3. Slice the STL file into thin cross-sectional layers
4. Construct the model one layer at another layer
5. Clean and finish the model

CAD Model Creation:

1. First, the object to be built is modeled using a Computer-Aided Design (CAD) software package.
2. Solid modelers, such as Pro/ENGINEER, tend to represent 3-D objects more accurately than wire-frame modelers such as AutoCAD, and will therefore yield better results.
3. This process is identical for all of the RP build techniques.

Conversion to STL Format:

4. To establish consistency, the STL (stereolithography, the first RP technique) format has been adopted as the standard of the rapid prototyping industry.
5. The second step, therefore, is to convert the CAD file into STL format. This format represents a three-dimensional surface as an assembly of planar triangles
6. STL files use planar elements, they cannot represent curved surfaces exactly. Increasing the number of triangles improves the approximation

Slice the STL File:

7. In the third step, a pre-processing program prepares the STL file to be built.
8. The pre-processing software slices the STL model into a number of layers from 0.01 mm to 0.7 mm thick, depending on the build technique.

9. The program may also generate an auxiliary structure to support the model during the build. Supports are useful for delicate features such as overhangs, internal cavities, and thin-walled sections.

Layer by Layer Construction:

10. The fourth step is the actual construction of the part.

11. RP machines build one layer at a time from polymers, paper, or powdered metal.

12. Most machines are fairly autonomous, needing little human intervention.

Clean and Finish:

13. The final step is post-processing. This involves removing the prototype from the machine and detaching any supports.

14. Some photosensitive materials need to be fully cured before use

15. Prototypes may also require minor cleaning and surface treatment.

16. Sanding, sealing, and/or painting the model will improve its appearance and durability.

Rapid Prototyping Techniques

Stereolithography

- Patented in 1986, stereolithography started the rapid prototyping revolution.
- The technique builds three-dimensional models from liquid photosensitive polymers that solidify when exposed to ultraviolet light.

The Stereolithography Machine

PT CAM uses a stereolithography machine produced by 3-D Systems and shown here:

Fused Deposition Modeling

- (FDM) is a solid-based rapid prototyping method that extrudes material, layer-by-layer, to build a model.
- A thread of plastic is fed into an extrusion head, where it is heated into a semi-liquid state and extruded through a very small hole onto the previous layer of material.
- Support material is also laid down in a similar manner.

Advantages of FDM

- High strength
- Cost-effective
- Waterproof
- Multiple material colors

Examples of FDM

In chemical machining maskants used

To protects surface

S. No	Parameters	Values ECM	
1	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	
2	Electrolyte		
	Material	NaCl and $NaNO_3$	
	Temperature	20 to 50 C	
	Flow Rate	20 lpm/100 A current	
	Pressure	0.5 to 20 bar	
	Dilution	100 g/l to 500 g/l	
3	Working Group	0.2 mm to 1 mm	
4	Overcut	0.2 mm to 3 mm	

5	Feed Rate	0.5mm/min to 15 mm/min	
6	Electrode Material	Copper, Brass and bronze	
7	Surface Roughness (Ra)	0.2 to 1.5 micro m(miu m)	