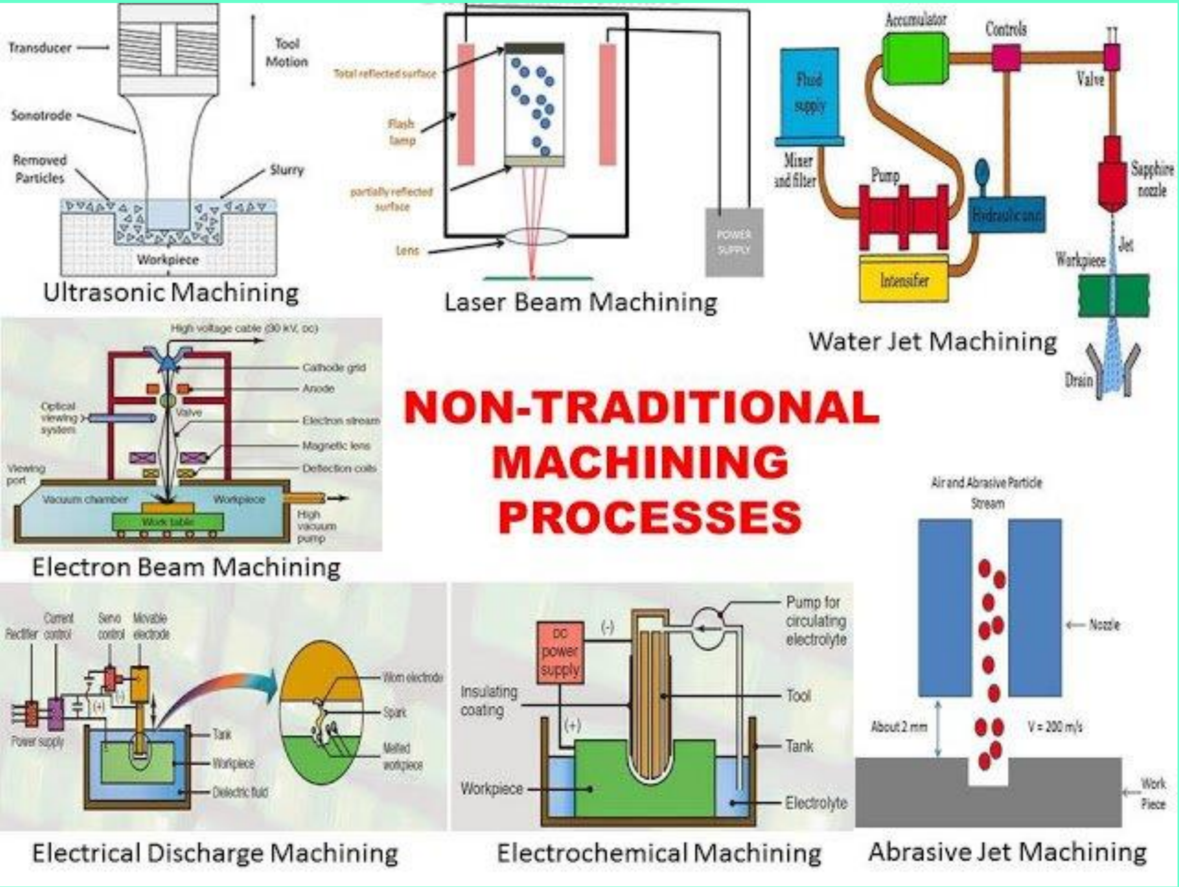
LECTURE-03: MODERN MACHINING PROCESSES



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Introduction

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

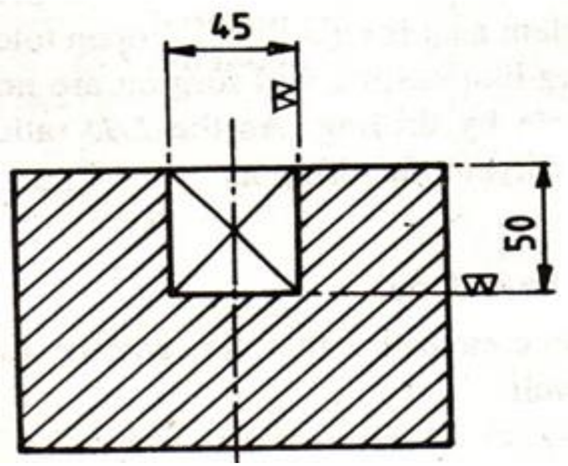
- Conventional machining processes (i.e., turning, drilling, milling, etc.) use a sharp cutting tool to form a chip from the work by shear deformation. In addition to these conventional methods, there is a group of processes that use other mechanisms to remove material.
- Modern machining refers to this group of processes, which remove excess material by various techniques involving mechanical, thermal, electrical, chemical energy or combinations of these energies. They do not use a sharp cutting tool in the conventional sense. The commercial and technological importance of the nontraditional processes, include:
- The need to machine newly developed metals and nonmetals. These new materials often have special properties (e.g., high strength, high hardness and high toughness) that make them difficult or impossible to machine by conventional methods.
- The needs for unusual and/or complex part geometries that cannot easily be accomplished and in some cases are impossible to achieve by conventional machining.
- The need to avoid surface damage that often accompanies the stresses raised by conventional machining.

Modern Manufacturing Processes

- Modern or Non-traditional manufacturing processes is 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 tools 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. Nontraditional machining processes, also called advanced manufacturing processes, are employed where traditional machining processes are not feasible, satisfactory or economical due to special reasons as outlined below.
    - Very hard fragile materials difficult to clamp for traditional machining
    - When the workpiece is too flexible or slender
    - When the shape of the part is too complex

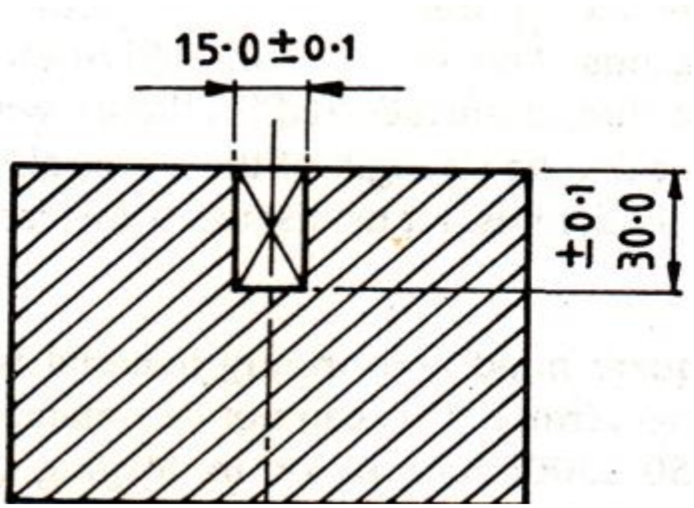
Needs for Modern Machining Processes

- The industries always face problems in manufacturing of components because of several reasons. This may be because of the complexity of the job profile or may be due to surface requirements with higher accuracy and surface finish or due to the strength of the materials. To elaborate such difficulties, let us discuss some case studies:
- Case-I: This is a case of a square blind hole in any material with higher surface finish of about 10 mμ. This can not be obtained in foundry (range of surface finish 1250-2250 mμ) or in forging (750-1250 mμ) practices. This has to be finished in a machine shop. If it is a case of single piece or a mass production-slotting or broaching of blind hole without a recess can not be done. For above reason, first a through hole drilling and then plugging to required length which increase the production time unnecessarily.



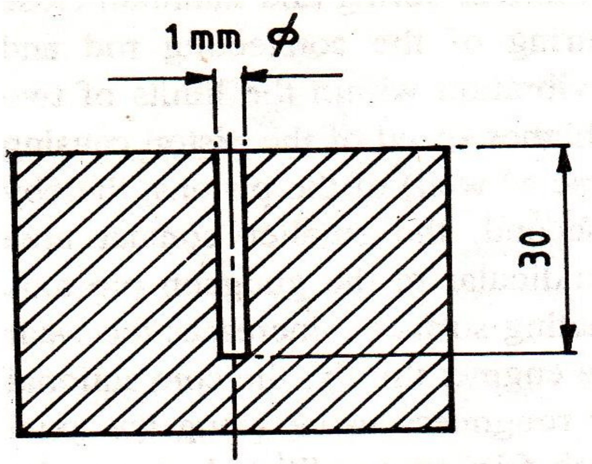
Square Blind Hole Manufacturing

- Case-II: Consider the same square hole machining with certain accuracy requirements. In this case, the preliminary processing will be either foundry or forging depending on the properties of the material, but can not give the desired accuracy even if we make the hole. To achieve accuracy we must go for machining using and end milling cutter, but then, there will be a restriction on the corner radius depending on the size of the cutter. Again, if the corner is milled by corner milling attachment then there is a restriction on the length to diameter ratio. This trouble is seen due to fact that the shape of the job and its accuracy pose problems in manufacturing.



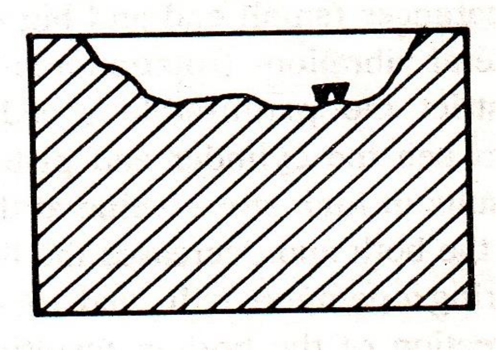
Square Hole Machining

- Case-III: Now let us considered the job of same material as above, where shape and accuracy is not a problem as it is circular with open tolerances. In this case preliminary processing like casting and forging are not possible, so final operation is to be done by drilling. As L/D ratio is more than 30, think of the difficulty in manufacturing as
  - The drill may break and
  - The hole may be inclined too. This results to the conclusion that the size of the job some times creates a problem as well.



Small Hole Drilling

- Case-IV: Now , consider a contoured hole generation in a very hard material like WC or satellite for making a die block. Any conventional machining excepting diamond contour grinding is not possible. The contour grinding will provide the lay line orientation along the feed direction resulting in inadequate lubrication between the die and blank because of the directional property of the lay lines, again, the profile errors of the die will be more due to the cross sensitivity factors of the 3D motion of the cutter. This increases production time (grinding is a low material removal process) since the other cutters (milling) do not have strength to machine these types of hard materials. So we can conclude that the increased strength of work material and inadequacy or complicacy of the control system (3D profiling) make it difficult to manufacture components to desired expectations.



Contoured Die Block

Classification of Modern Machining Processes

- The modern machining processes are often classified according to principal form of energy used to effect material removal. By this classification, there are four types:
  - Mechanical Processes: Mechanical energy in some form different from the action of a conventional cutting tool is used in these nontraditional processes. Erosion of the work material by a high velocity stream of abrasives or fluid (or both) is the typical form of mechanical action in these processes.
  - Electrical Processes: These nontraditional processes use electrochemical energy to remove material; the mechanism is the reverse of electroplating.
  - Thermal Processes: These processes use thermal energy to cut or shape the workpart. The thermal energy is generally 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 the conversion of electrical energy.
  - Chemical Etching Processes: Most materials (in particular, metals) are susceptible to chemical attack by certain acids or other etchants. In chemical machining, chemicals selectively remove material from portions of the workpart, while other portions of the surface are protected by a mask.

- Modern or Unconventional or Nontraditional machining processes are classified depending on the type of energies as:

Modern Machining

Mechanical Energy [Mechanical Processes]	
Abrasive Jet Machining	**AJM**
Water Jet Machining	**WJM**
Ultrasonic Machining	**USM**
Ultrasonic Assisted Machining	**UAM**
Abrasive Flow Machining	**AFM**

Electrical Energy [Electrical Processes]	
Electrochemical Machining	**ECM**
Electrochemical Grinding	**EGD**
Electrochemical Deburring	**ECD**
Electrochemical Honing	**ECH**
Electrostream Drilling	**ESD**

Thermal Energy [Thermal Processes]	
Electrodischarge Machining	**EDM**
Electron Bean Machining	**EBM**
Laser Beam Machining	**LBM**
Plasma Arc Machining	**PAM**
Ion Beam Machining	**IBM**

Chemical Energy [Chemical Etching Processes]	
Chemical Milling	**CHM**
Chemical Blanking	**CHB**
Chemical Engraving	**CHE**
Electropolishing	**ELP**
Photo Chemical Machining	**PCM**

Process Variables of Modern Machining Processes

- To make efficient use of modern machining processes, it is necessary to know the exact nature of the machining problem. It is to be understood that
    - these methods cannot replace the conventional machining processes
    - a particular machining method found suitable under the given conditions may not be equally efficient under other conditions.
- A careful selection of the process for a given machining problem is, therefore, essential. Before selecting the process to be employed, the following aspects must be studied:
    - Physical parameters
    - Properties of the work material and the shape to be machined
    - Process capability
    - Economic considerations.

Characteristic Features of Modern Machining Processes

- The following are the characteristic features of modern machining processes when compared with traditional or conventional machining processes:
  - Material is removed from the work piece without mechanical contact (with work piece).
  - In many processes, material removal rate is independent of the hardness of the work piece.
  - Cutting forces are independent of the hardness of the work material.
  - The tool material need not be harder than the work material.(In many cases, softer materials can be used as tool material)
  - Almost any work material irrespective of its hardness and strength can be machined.
  - Generally tool wear is negligible; hence tool wear is not a problem.
  - No burr is left on the work piece.

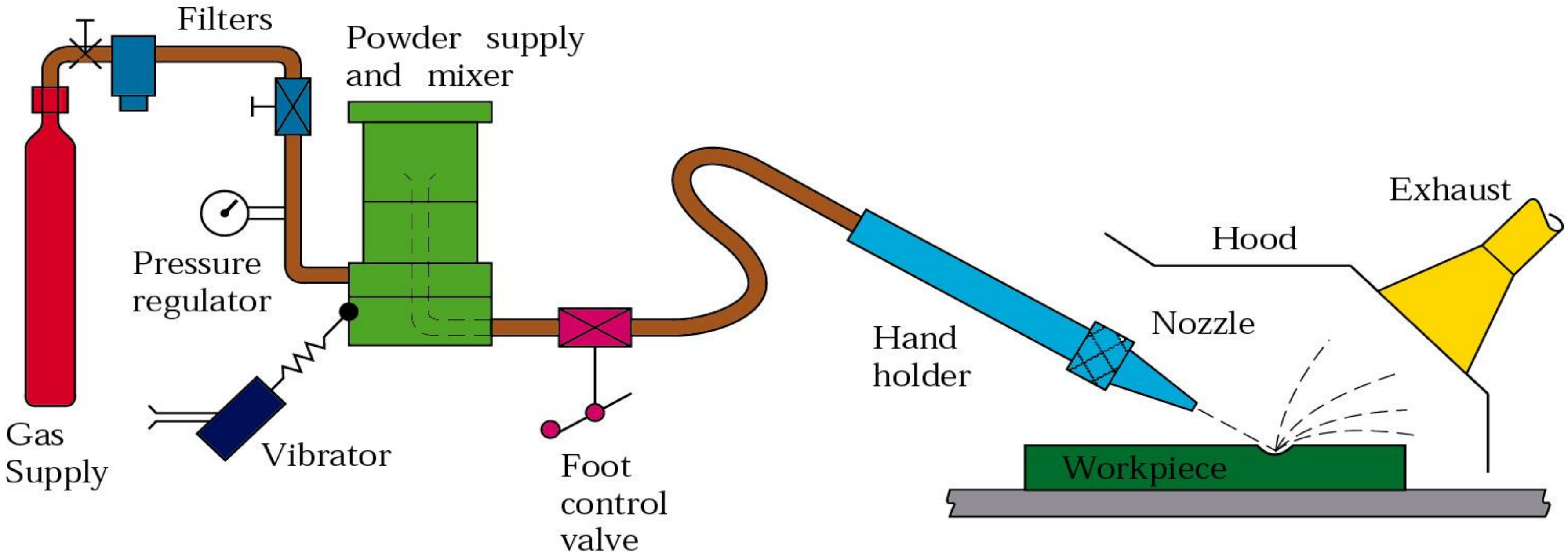
- Generally no residual stresses are left on the surfaces machined.
- In most of the cases entire shape can be obtained in one stage or in one setting. This is possible since material removal takes place uniformly over the entire area below the tool simultaneously.
- In majority of cases surface integrity (Surface integrity is the surface condition of a work piece after being modified by a manufacturing process.) of the surfaces produced by modern machining methods is superior.
- Modern machining methods can be integrated easily with micro-processors and numeric controls for better control of the processes and for improving the versatility and productivity of the machines.
- Intricately shaped contours and fine machining of precision holes are possible.

- Economical considerations to be studied before going for Modern Machining:
  - High cost of equipment, which typically includes computer control
  - May use hard tooling, soft tooling, or both
  - Low production rates
  - Can be used with difficult-to-machine materials
  - Highly repeatable
  - Typically requires highly skilled operators
- Modern machining processes typically have lower feed rates and require more power consumption when compared to machining. However, some processes permit batch processing which increases the overall throughput of these processes and enables them to compete with machining.

Abrasive Jet Machining (AJM)

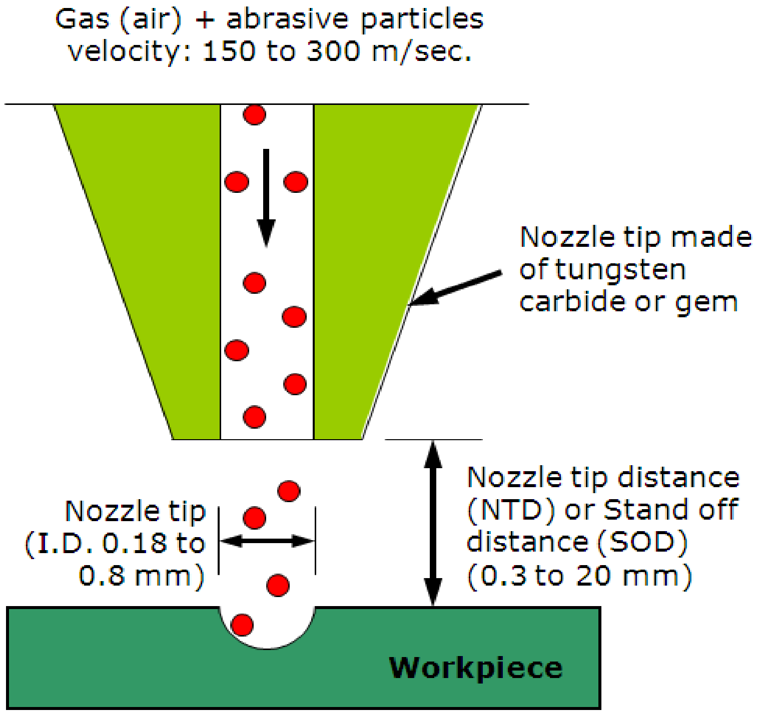
- In this process, a focused steam of abrasive particles (of size 10 to 40 microns) carried by high pressure gas or air at a velocity of about 150 to 300 m/sec is made to impinge on the work surface through a nozzle, and the work material is removed by erosion by the high velocity abrasive particles. The inside diameter of the nozzle through which abrasive particles flow is about 0.18 to 0.80 mm and the stand-off distance (i.e. distance between nozzle tip and workpiece) is kept about 0.3 to 20.0 mm.
- The process can be easily controlled to vary the metal removal rate which depends on flow rate and size of abrasive particles. This process is best suited for machining super alloys and refractory type of materials, and also machining thin sections of hard materials and making intricate hard holes. The cutting action is cool because the carrier gas serves as coolant.
- When an abrasive particle (like Al2O3 or SiC) having sharp edges hits a brittle and fragile material with a high speed, it makes dent into the material and lodges a small particle from it by a tiny brittle fracture. The lodged out or wear particle is carried away by the air or gas. The operating elements in AJM are abrasive, carrier gas and the nozzle as schematically shown in the following Figure.

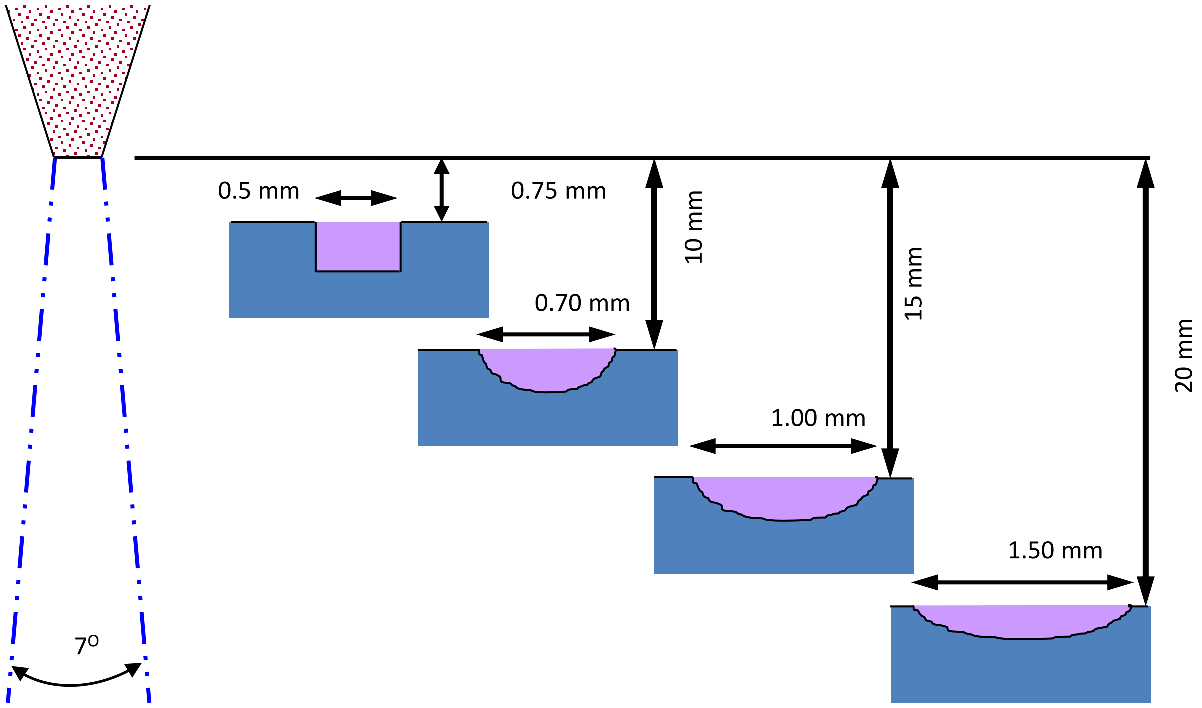
- The basic unit consists of gas supply system (compressor), filter, pressure regulator, mixing chamber, nozzle assembly and the work holding device. In the mixing chamber, the abrasive is allowed to flow into the gas stream. The mixing ratio is generally controlled by a vibrator. The particle and gas mixture comes out of the nozzle inside the machining chamber of the machine tool unit. The feed motion can be given either to the work holding device or to the nozzle.



Effect of SOD on Machining Accuracy

The distance between the nozzle tip and the work surface has great influence on the diameter of cut, its shape and size and also rate of material removal. The following **Figure** shows the variation in the diameter of cut with change in the stand off distance (SOD). It is evident that the SOD changes the abrasive particles spreads (i.e. covers wider area) on the work surface and consequently increases the diameter of the cut.



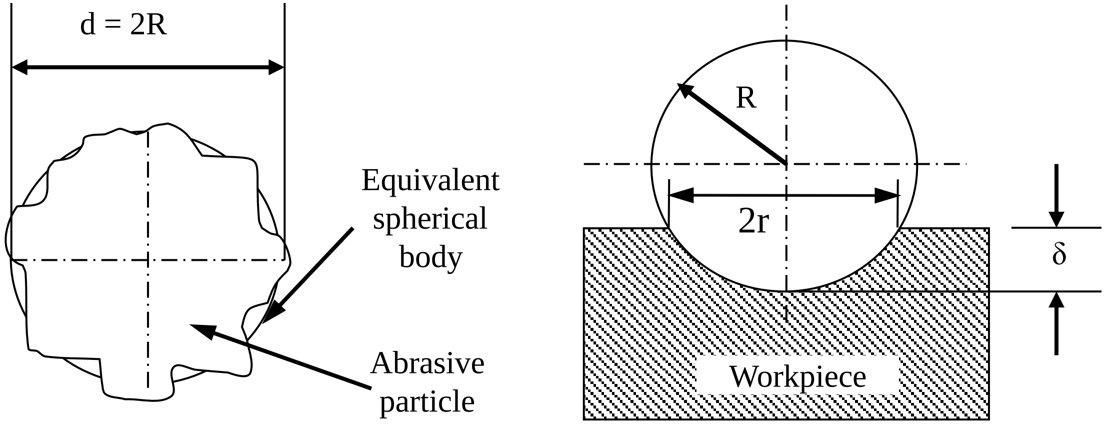


Material Removal Rate (MRR)

The material is removed from work piece due to impact erosion of the high velocity particles. The Kinetic Energy of the particle is utilized to cause the micro-indentation in the work material and the material removal is a measure of the indentation. The model is based on the following assumptions:

- The abrasive particles are considered to be rigid and spherical bodies of diameter equal to the average grit size.
- The material removed is equal to the volume of material removed is hemispherical whose diameter is equal to the chord length of the indentation.

r = half of the chord length
d = average diameter of the particle
δ = indentation depth

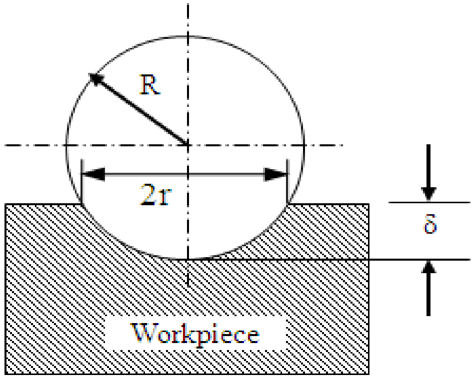


Scheme of Material Removal Mechanism

$$R^2 = (R-\delta)^2 + r^2 = R^2 - 2R\delta + \delta^2 + r^2$$

Neglecting δ^2 terms

$$r^2 = 2R\delta = d\delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$



So the volumetric material removal per particle impact ν is given by:

For Brittle materials (hemispherical brittle fracture)

$$\nu\ (\text{brittle}) = \frac{1}{2}\left(\frac{4}{3}\pi r^3\right) = \frac{2}{3}\pi r^3 = \frac{2}{3}\pi(d\delta)^{\frac{3}{2}} \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

For ductile work material (material removal is equal to the indentation volume)

$$\nu\ (\text{ductile}) = \pi\delta^2\left[\frac{d}{2} - \frac{\delta}{3}\right]$$, and neglecting δ^3

$$\nu\ (\text{ductile}) = \left(\frac{\pi d\delta^2}{2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

So, if there are N number of particles impacts per unit time, the material removal rate (MRR) equations are obtained from Equations (2) & (3)

$$\text{MRR (brittle)} = \frac{2}{3}\pi(d\delta)^{\frac{3}{2}}N \text{ ....}(4)$$

$$\text{MRR (ductile)} = \left(\frac{\pi d\delta^2}{2}\right) N \text{ ....}(5)$$

The unknown factors in the above two equations are δ and N. The estimation of δ can be derived from the energy balance equation as

K.E.=W.D. in the indentation of work material.

Now K.E. possessed by the particle of mass **m** and density **ρ**, moving with a velocity **V** just before the impact is,

$$\text{K.E.} = \frac{1}{2}mV^2 = \frac{1}{2}\left[\frac{\pi}{6}d^3\rho\right]V^2 = \frac{\pi}{12}d^3\rho V^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

The energy of impact will introduce a force **F** on the indenter to cause an indentation depth **δ** in work material of hardness **H**. So W.D. in the indentation

$$\text{W.D.} = \frac{1}{2}F\delta = \frac{1}{2}(\pi r^2 H)\delta = \frac{1}{2}(\pi d\delta H)\delta \text{ ....}(7)$$

From equation (6) and equation (7)

$$\frac{\pi}{12}d^3\rho V^2 = \frac{1}{2}(\pi d\delta H)\delta$$

$$\delta^2 = \frac{\rho}{6}\left[\frac{(dV)^2}{H}\right] \text{...}(8)$$

The number of particles **N** striking the target can be estimated from the known value of abrasive mass flow rate, **M** as

$$N = \frac{M}{\text{Mass of each particle}} = \frac{6M}{\pi d^3\rho} \text{...............................}(9)$$

- The MRR equation can be determined by substituting the values δ and N in equations (4) and (5)
- $\mathrm{MRR(brittle)} = 1.04\frac{\mathrm{MV}^{\frac{3}{2}}}{\rho^{\frac{1}{4}}\mathrm{H}^{\frac{3}{4}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$

Similarly for ductile materials,

- $\mathrm{MRR(ductile)} = 0.5\frac{\mathrm{MV}^{2}}{\mathrm{H}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (11)$
- Equations (10) and (11) give the maximum possible material removal rate in case of AJM process for machining brittle materials and ductile materials respectively. The equations show that the velocity effects are more predominant than mass flow rate on material removal rate.

Variables of AJM

The variables that influence the rate of metal removal and accuracy of the machining in this process are:

- Carrier gas
- Type of abrasive
- Size of the abrasive grain
- Velocity of the abrasive jet
- Mean number of abrasive particles per unit volume of the carrier gas
- Work material
- Stand off distance (SOD)
- Nozzle design
- Shape of cut

Advantages, Limitations and Applications of AJM

- Advantages of AJM
  - This process is quite suitable for machining brittle, heat resistant and fragile materials
  - It can be utilized for cutting, drilling, polishing, deburring, cleaning etc. of the materials
  - The depth of damage to the surface is very little
  - Holes of intricate shapes could be produced efficiently
  - The surface machined can have good finish.
- Limitations of AJM
  - The materials removal rate is low. For example, for glass, it is 0.0164 cm^3/min
  - Elastomers or soft plastics are mot amenable to abrasive jet treatment
  - The tapering of hole especially, when the depth of the hole is more, becomes almost inevitable

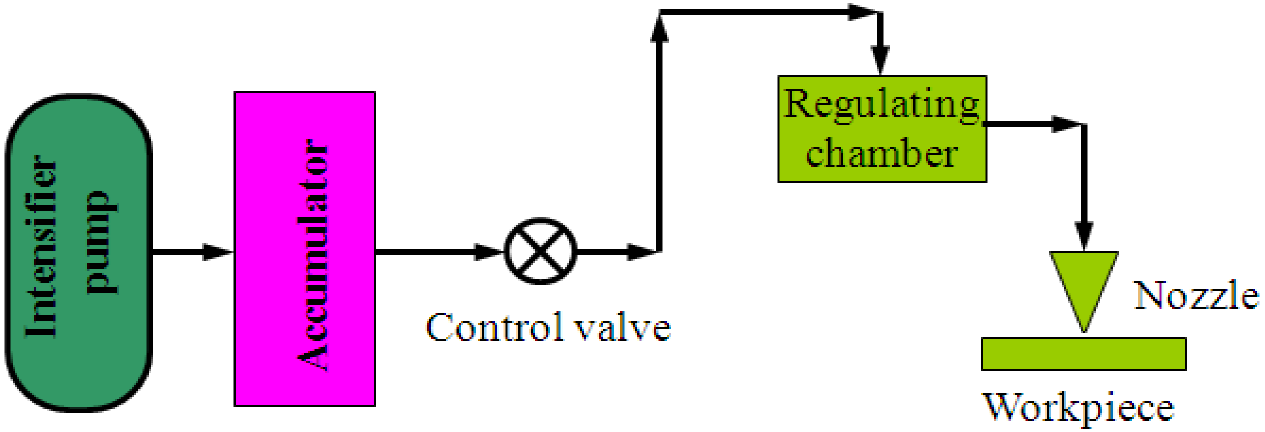
  - A dust collecting chamber is a basic requirement to prevent atmospheric pollution to cause health hazards
  - The abrasive particles may remain embedded in the work surface
  - Abrasive particles cannot be reused
- Applications of AJM
  - This is used for abrading and frosting glass more economically as compared to etching or grinding
  - Cleaning of metallic smears on ceramics, oxides on metals, resistive coatings etc.
  - Cutting and machining of fragile material like germanium, silicon etc
  - Register treaming can be done very easily and micro module fabrication for electrical contact, semiconductor processing can also be done effectively
  - It is a good method for deburring small hole like in hypodermic needles and for small milled slots in hard metallic components.

Summary of AJM Characteristics

- Mechanics of material removal - brittle fracture by impinging abrasive grains at high speed
- Media - Air, CO_2
- Abrasives: Al_2O_3, SiC, 0.025mm diameter, 2-20g/min, non-recirculating
- Velocity = 150-300 m/sec
- Pressure = 2 to 10 atm.
- Nozzle-WC, sapphire, orifice area 0.05-0.2 mm^2, life 12-300 hr., nozzle tip distance 0.25-75 mm
- Critical parameters - abrasive flow rate and velocity, nozzle tip distance from work surface, abrasive grain size and jet inclination
- Materials application-hard and brittle metals, alloys, and nonmetallic materials (i.e. germanium, silicon, glass, ceramics, and mica). Specially suitable for thin sections
- Shape (job) application - drilling, cutting, deburring, etching, cleaning
- Limitations - low metal removal rate (40 mg/min, 15 mm^3/min), embedding of abrasive in workpiece, tapering of drilled holes, possibility of stray abrasive action.

Water Jet Machining (WJM)

- Water jets alone (without abrasive) can be used for cutting. Thin jets of high pressure and high velocity have been used to cut materials such as wood, coal, textiles, rubber, rocks, concrete, asbestos and leather.
- The method has also now been used for hydraulic mining of coal, tunneling and cleaning and descaling operation. Also, automated deburring machines are being used by the automotive industry. As mentioned above, the mechanism of material removal is by erosion.
- When high pressure water jet emerges out of a nozzle, it attains a large kinetic energy. When this high velocity jet strikes the workpiece, its kinetic energy is converted into pressure energy inducing high stresses in the work material. When the induced stress exceeds the ultimate shear stress of the material, rupture takes place. The limitations of the WJM is the high initial cost.



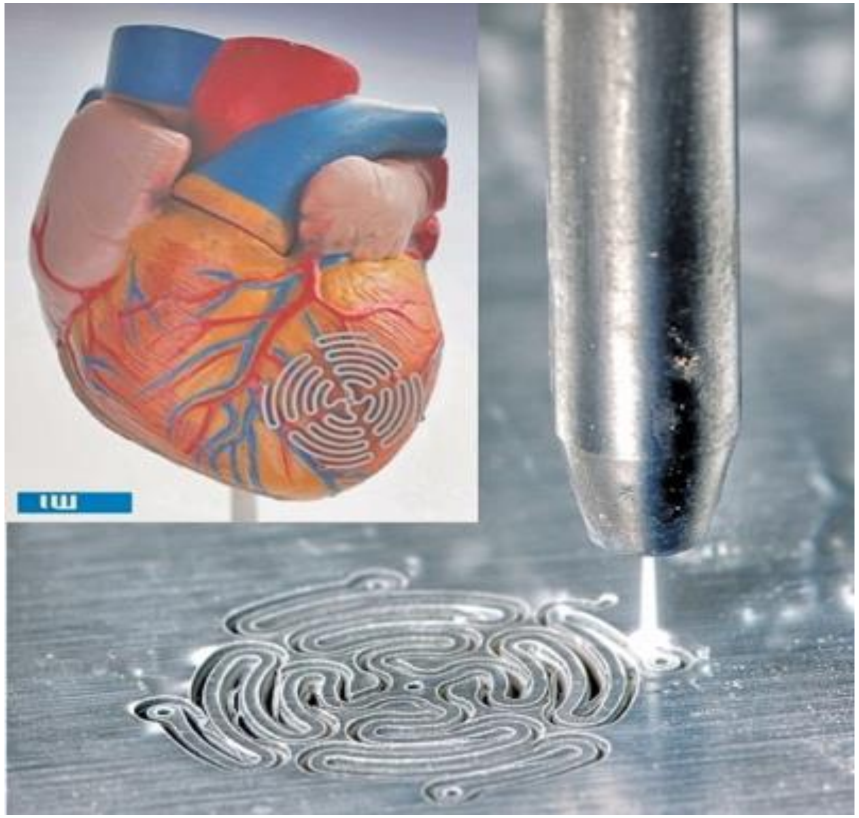
Schematic diagram of WJM setup

- Intensifier Pump
  - basically a small piston driven by a larger hydraulic piston. The opposing cylinders change a large differential volume for a large differential pressure.
  - as the hydraulic unit in the center pumps in both directions, a high pressure is generated in the water cylinders at either end. Check valves allow water flow in and out as appropriate.
  - the pressures generated by the intensifier can be adjusted by modifying the hydraulic pressures.
- Accumulator
  - Acts as a pressurized reservoir for the water.
- Tubing and Fittings
  - between the accumulator, and the movable head, a variable dimension delivery system is required.
  - at lower pressures flexible rubber hoses would be used, but at these pressures, a coiled stainless steel tube is often used. The ends of the tubes are connected with high pressure swivels.
  - a protective sheath is placed about the tubes to prevent damage in the instance of leaks. Flow valves are also used to reduce the chances of damage.

Advantages and Applications of WJM

- Advantages of WJM
  - Water is cheap, non-toxic, readily available and can be easily disposed
  - Water jet approaches the ideal single point tool
  - The process gives a clean and sharp cut
  - Best suited for explosive environments
  - Dustless atmosphere-this is particularly advantages for cutting asbestos and glass fiber insulation materials which produced dust
  - Noise is minimized as the power units and pumps can be kept away from the cutting point
  - No moving parts are present and, therefore, less maintenance is required
  - Jet takes away all the cutting residue and hence there are no pollution problems
  - Fluid can be reused by filtering out the solids
- Applications of WJM
  - WJM is used to cut many nonmetallic materials like Keplar, glass, epoxy, graphite, corrugated board, FRP (Fiber-Reinforced Plastic), leather and many other brittle materials.
  - It is used in shoe making industry and now has entered into steel plant to descale the chilled layer of steel ingots, in aircraft industries to profile cutting of FRP (Fiber-Reinforced Plastic) aircraft structures even glass windows.

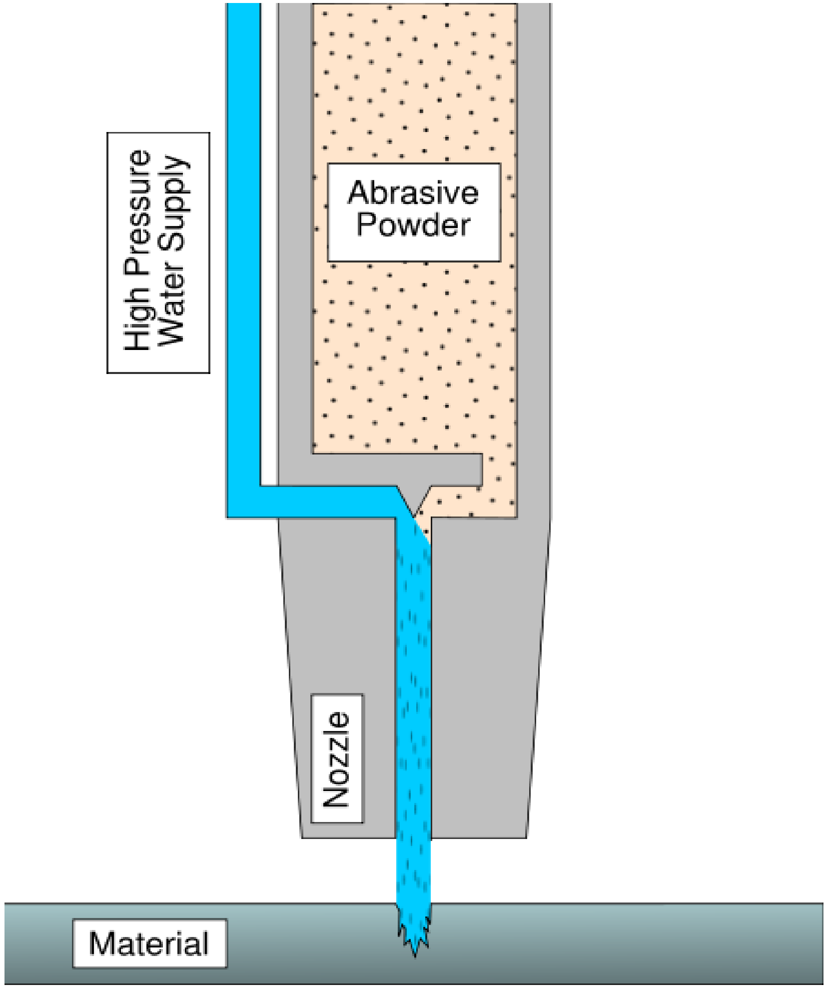
Different engineering components machined with AWJ



Cutting a prototype heart patch reinforcement

Abrasive Water Jet Machining

- Abrasive water jet cutting differs from pure water jet cutting in just a few ways. In pure water jet cutting, the supersonic stream erodes the material.
- In the abrasive water jet, the water jet stream accelerates abrasive particles and those particles, not the water, erode the material.
- The abrasive water jet is hundreds, if not thousands of times more powerful than a pure water jet. Both the water jet and the abrasive water jet have their place. Where the pure water jet cuts soft materials, the abrasive water jet cuts hard materials, such as metals, stone, composites and ceramics.
- Abrasive water jets using standard parameters can cut materials with hardness up to and slightly beyond aluminum oxide ceramic

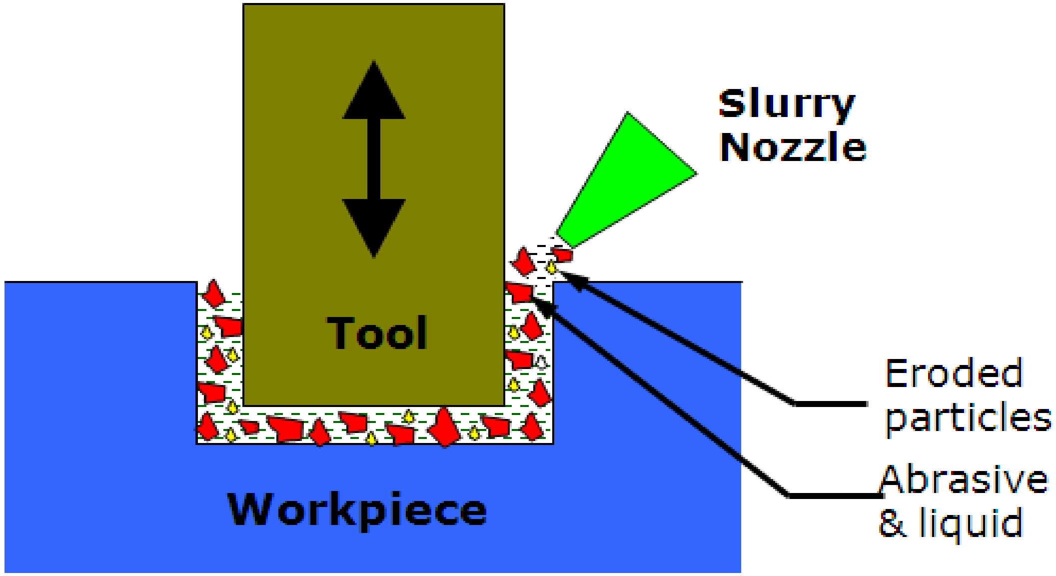


Advantages and Applications of AWJM

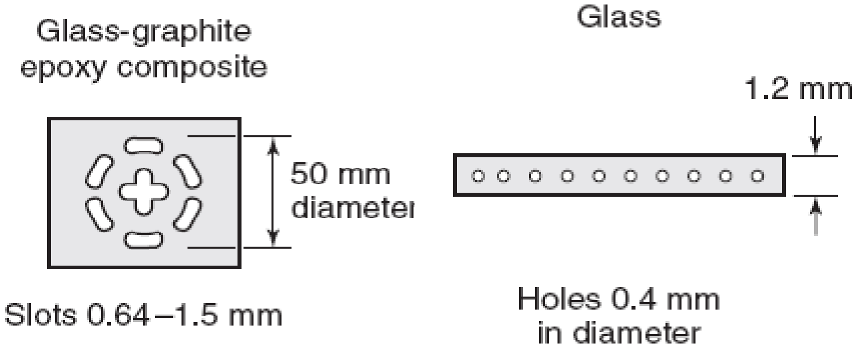
- Advantages of AWJM
  - Cheaper than other processes.
  - Cut virtually any material. (pre hardened steel, mild steel, copper, brass, aluminum; brittle materials like glass, ceramic, quartz, stone)
  - Cut thin stuff, or thick stuff.
  - Make all sorts of shapes with only one tool.
  - No heat generated.
  - Leaves a satin smooth finish, thus reducing secondary operations.
  - Clean cutting process without gasses or oils.
  - Machine stacks of thin parts all at once.
- Applications of AWJM
  - Cutting of difficult-to-machine materials by abrasive water jets
  - Milling and 3-D-shaping by abrasive water jets
  - Turning by abrasive water jets
  - Piercing and drilling by abrasive water jets
  - Polishing by abrasive water jets

Ultrasonic Machining (USM)

- This is an impact erosion process to machine materials where the work material is removed by repetitive impact of abrasive particles carried in a liquid medium in the form of slurry under the action of a shaped vibrating tool attached to a vibrating mechanical system horn. The word shaped explains that the process in capable of producing 3D profiles corresponding to the tool shape unlike AJM process. Basic scheme is as shown in the following Figure.

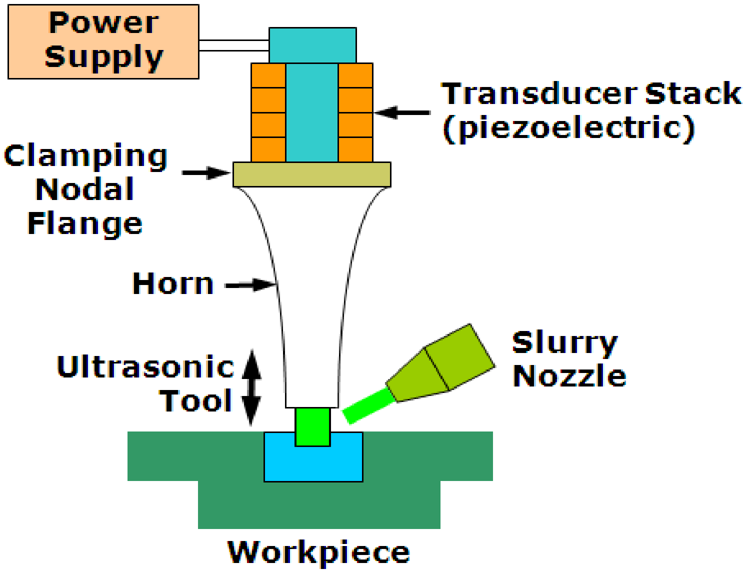


Ultrasonic Machining



Working Principle of USM

- The working principle is schematically shown in the following **Figure**, where a shaped tool is given a mechanical vibration. This vibration causes the abrasive particles in the slurry to hammer against a stationary workpiece to cause micro-indentation to initiate fracture in work material, observed as stock removal of the latter.
- The minute particles of abraded material are removed along the surface perpendicular to the direction of the tool vibrations. As the material is removed, a cavity is formed in the piece, exactly copying the profile of the tool face.



During the machining operation the abrasive particles participating in the operation gradually erode, hence a liquid is fed into the machining zone, where it supplies fresh abrasive grains and ensures the removal of the spent grains and material particles. Thus, the ultrasonic machine tool must provide for vibrations of the tool at large amplitude (5~75 μm) and a given frequency (19~25 kHz), and it must supply the required static force to hold the tool against the work piece and a continuous flow of abrasive suspension into the machining zone.

Material Removal Rate (MRR)

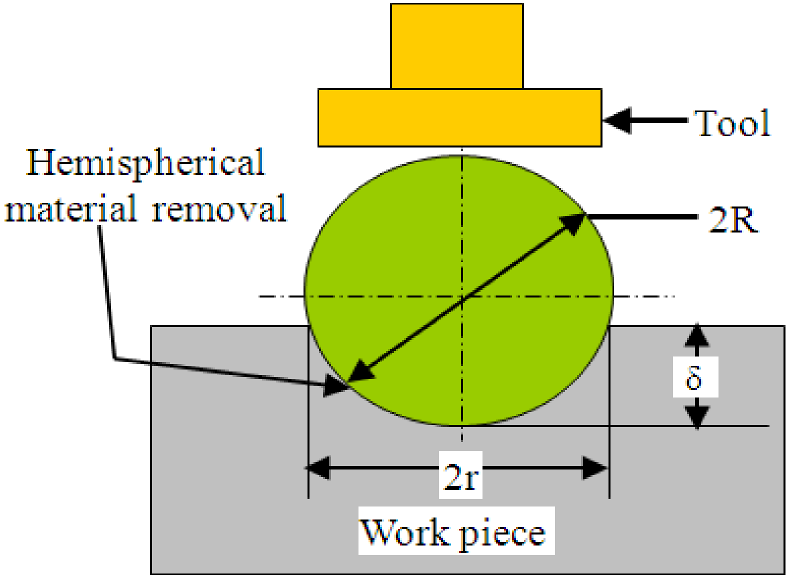
This method is based on the brittle fracture of the work materials and under following assumptions:

- The abrasive grits are spherical in nature
- Material removal is based on hemispherical fracture mechanism due to the indentation
- Tool and abrasive are rigid.

If R is the radius of the abrasive grit, r is the radius of circular indentation and H is the hardness of the work material, then the volume of the material removal per impact υ is given by

$$\upsilon = \frac{1}{2}\left(\frac{4}{3}\pi r^3\right) = \frac{2}{3}\pi r^3 \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\text{Hence MRR/grit} = \upsilon.f = \frac{2}{3}\pi r^3.f \ldots\ldots\ldots\ldots\ldots (2)$$



Where,

r = radius of circular indentation

f = frequency of operation

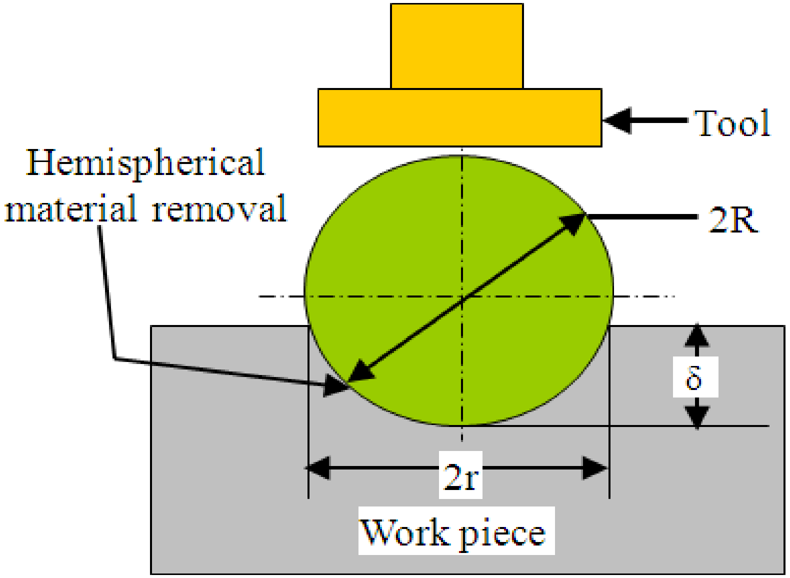
N = number of grit per unit area

From the geometry of the following figure

$$R^2 = (R-\delta)^2 + r^2 = R^2 - 2R\delta + \delta^2 + r^2$$

Neglecting δ^2 terms

$$r^2 = 2R\delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$



From equation (2) and (3)

$$\text{MRR/grit} = \frac{2}{3}\pi(2R\delta)^{\frac{3}{2}} \times f \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

If there are N number of grits per unit area, then total

$$\text{MRR} = \frac{2}{3}\pi(2R\delta)^{\frac{3}{2}} \times f \times N \ldots\ldots\ldots\ldots(5)$$

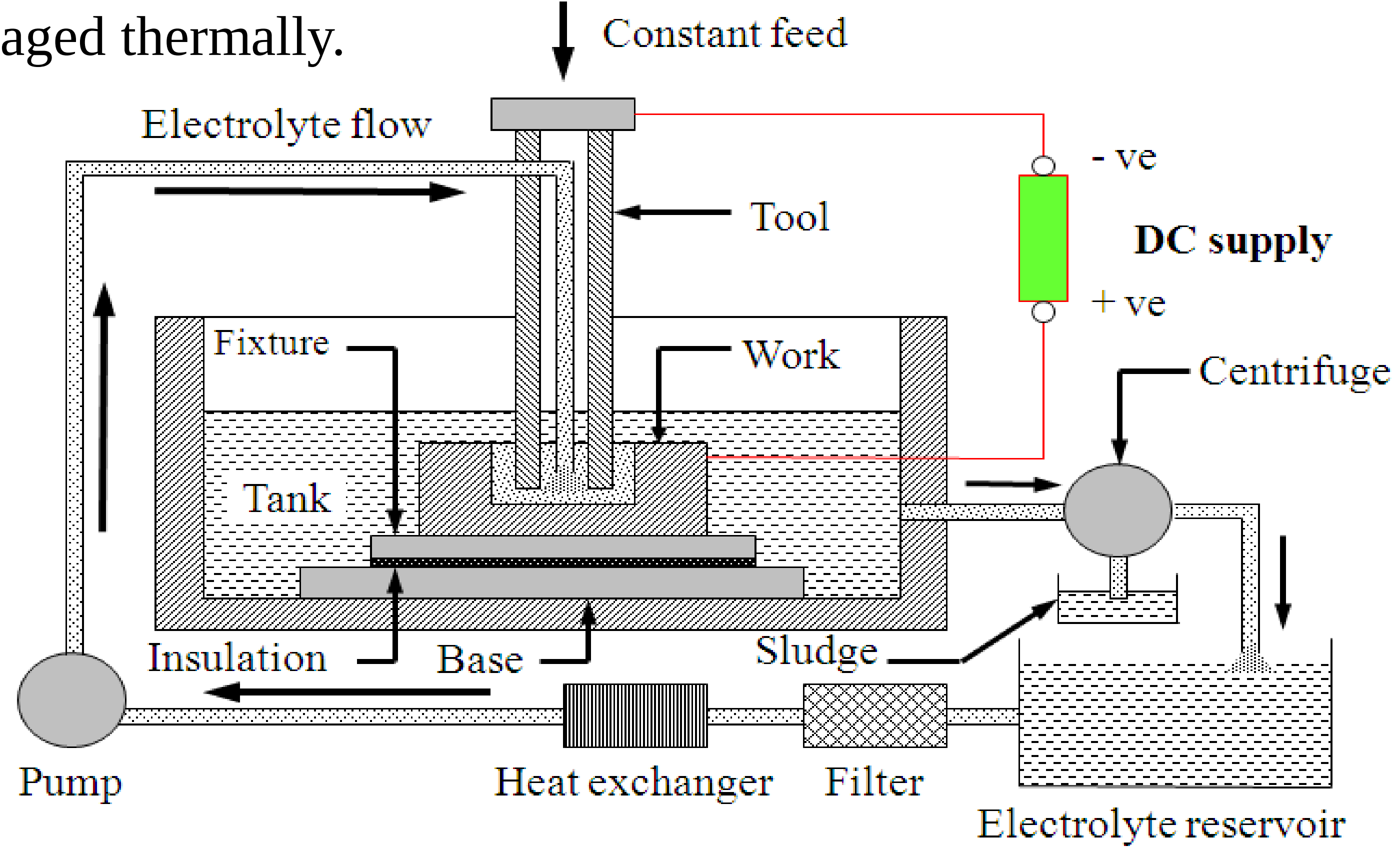
Advantages, Limitations and Applications of USM

- Advantages of USM
  - This process can be used for drilling of circular or non-circular holes in very hard materials like stones, carbide, ceramics and exceptionally brittle materials
  - The metal to be machined may be non-conducting of the electricity, such as glass, ceramics and semi-precious stones.
- Limitations of USM
  - Low machining rates are achievable as compared to the conventional machining.
  - It is difficult to machine very deep holes, as the slurry movement is restricted.
  - It is difficult to design the correct size of the tool to get exact dimensions on the job. There is high tool wear in the process.
- Applications of USM
  - For machining of hard and brittle materials that cannot be machined by conventional means. Difficult to machine materials include glass, diamond and tungsten carbide, etc. Wire drawing dies of tungsten carbide are drilled by using the USM process
  - For machining of circular and non-circular holes with straight or curved axes.
  - It has also been successfully used for machining of geranium, silicon, ceramics, carbon plates, quartz, tool steel, synthetic ruby, etc.

Electrochemical Machining (ECM)

- Electrochemical Machining is the controlled removal of metal by anodic dissolution in an electrolytic medium. It is based upon Faraday's law of electrolysis. In this process the workpiece acts as the anode and the tool as cathode. The two electrodes are closely placed, with a gap of about 0.5 mm, and immersed in an electrolyte (generally a solution of sodium chloride).
- When a potential difference is maintained between the electrodes, the ions existing in the electrolyte migrate towards them. Positively charged ions are attached towards the cathode and negatively charged ions are attached towards the anode. This initiates the flow of current in the electrolyte. The work is generally kept stationary and the tool is fed in a linear direction. The metal from the work is removed due to ion migration towards the tool.
- The tool is prevented from damage by pumping a strong stream of electrolyte at high pressure (15kg/cm^2). No spark is produced in this process and the temperature generate is low enough to cause any metallurgical changes in the workpiece.

- In this case, the tool does not come in contact with the workpiece, and the wear and tear of the tool is negligible. Machining takes place at low voltage and the metal removal rate is high. Dimension up to 0.05 mm can be easily controlled and the metal workpiece in not damaged thermally.



Schematic Diagram of Electrochemical Drilling Machine

Material Removal Rate (MRR)

- According to the Faraday’s first law of electrolysis, the amount of chemical changes, M produced (i.e. dissolved or deposited) is proportional to the amount of charge C passed through the electrolyte, i.e.

  $M \propto C$----------(1)

  The second law proposes that the amount of charge, **M** produced in the material is proportional to its electrochemical equivalent, **Z** of the material, i.e.

  $M \propto Z$----------(2)

  From equation (1) and (2)

  $$M \propto C \times Z = \frac{1}{F} C \times Z \quad \text{........................(3)}$$

  M= mass of ions dissolved or deposited

  C= Charge

  Z= Constant (is known as electro-chemical equivalent of the substance)

  F= Faraday’s constant

- The value of Z depends on atomic weight and valency of the ions and is given by

$$Z = \frac{\text{Atomic weight of the material in gm}}{\text{Valency of metal dissolved}} = \frac{A_w}{\upsilon} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

From equation (3) and (4)

$$M = \frac{1}{F}(I.t)\left(\frac{A_w}{\upsilon}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The material removal rate in term of height of the metal removed per unit time can be obtained in the following manner:

$$M = a \times h \times \rho \times t \ \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where,

a = machined area

h = height of the metal removed

ρ = density of the metal

C= Charge= I. t

I= Current flowing through the electrolytic cell in amperes

t= Time in sec

- Therefore, the metal removal rate (MRR) (in term of height of metal removed per unit time) is given by

$$\mathrm{MRR} = \frac{M}{a\ \rho\ t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

  From equation (5) and (7)

$$\mathrm{MRR} = \frac{A_w\ I\ t}{F\ \upsilon\ a\ \rho\ t} = \frac{A_w\ I}{F\ \upsilon\ a\ \rho} \quad \mathrm{cm/sec} \quad = \frac{A_w\ I}{F\ \upsilon\ \rho} \quad \mathrm{cm^3/sec} - - - - - (8)$$

  Where F is the Faraday's constant = 96500 coulombs=26.8 amp.hr, C is the charge (coulomb), I is the current (ampere) and t is the dissolution period.

- Equation (8) gives the idea about the rate of dissolution of a **single elemental material**. Since most of the materials machined by this processes are difficult-to-machine alloys of metals, the Faradic equation (8) needs modification accordingly.

Metal Removal Rate of an Alloy

- Generally an engineering material is in the form of an alloy consisting of different elements. So to find out the rate of dissolution, one must consider each element separately and combine them for the whole alloy. To start with, let us consider the alloy consisting of:

  1-n = number of elements

  $A_{w1} \ldots A_{wn}$ = atomic weights of individual elements

  $\upsilon_1 \ldots\ldots \upsilon_n$ = valency of the respective elements

  $p_1 \ldots\ldots\ldots p_n$ = percentage of the element present in the alloy

  ρ = density of the alloy and

  V_a = volume of the alloy under consideration.

  The weight (M) of first element present in the alloy is given by

  $$M_1 = \frac{V_a\ \rho\ p_1}{100}\ \text{gm}$$

  Similarly, $M_2 = \frac{V_a\ \rho\ p_2}{100}$ gm ....$M_n = \frac{V_a\ \rho\ p_n}{100}$ gm, and so on

- The charge (quantity of electricity) required to dissolve the first element present in the alloy is given by

$$C_1 = \frac{M_1.F.\upsilon_1}{A_{w1}} = \frac{V_a \ \rho \ p_1}{100} . \frac{F \ .\upsilon_1}{A_{w1}}$$

Similarly, $C_2 = \frac{V_a \ \rho \ p_2}{100} . \frac{F \ .\upsilon_2}{A_{w2}}$........ $C_n = \frac{V_a \ \rho \ p_n}{100} . \frac{F \ .\upsilon_n}{A_{wn}}$ and so on

The total charge for removing all the elements from the alloys will be

$$C_{total} = C_1 + C_2 + C_3 + C_4 + \ldots\ldots\ldots\ldots C_n$$

$$= \frac{V_a \ \rho \ F}{100} \left[\frac{p_1 \ \upsilon_1}{A_{w1}} + \frac{p_2 \ \upsilon_2}{A_{w2}} + \frac{p_3 \ \upsilon_3}{A_{w3}} + \frac{p_4 \ \upsilon_4}{A_{w4}} \ldots\ldots\ldots \frac{p_n \ \upsilon_n}{An} \right]$$

$$C_{total} = \frac{V_a \ \rho \ F}{100} \sum_{i=1}^{i=n} \frac{p_i \ \upsilon_i}{A_{wi}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

- Hence the volumetric metal removal rate(V_m) per unit charge is given by

$$V_m = \frac{V_a}{C_{total}} = \frac{100}{\rho\ F} \frac{1}{\sum_{i=1}^{i=n} \frac{p_i\ \upsilon_i}{A_{wi}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

If current I flows for time t sec, then from equation (1)

$$C_{total} = It = \frac{V_a\ \rho\ F}{100} \sum_{i=1}^{i=n} \frac{p_i\ \upsilon_i}{A_{wi}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$MRR = \frac{V_a}{t} = \frac{100}{\rho\ F} \frac{I}{\sum_{i=1}^{i=n} \frac{p_i\ \upsilon_i}{A_{wi}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Electrolytes

- Functions of electrolytes
    - It carries the current between the tool and the work piece
    - It removes the product of machining from the cutting region
    - It dissipates heat produced in the operation
    - It helps the machining reactions necessary for anodic dissolution to take place
- Choice of proper electrolyte is of vital importance on the following considerations:
    - Machining rate
    - Dimensional accuracy
    - Surface texture and
    - Surface integrity
- Electrolyte should possess the following characteristics:
    - It should have high electrical conductivity
    - It should machine at high current efficiency
    - It should produce good surface finish and integrity

Advantages and Disadvantages of ECM

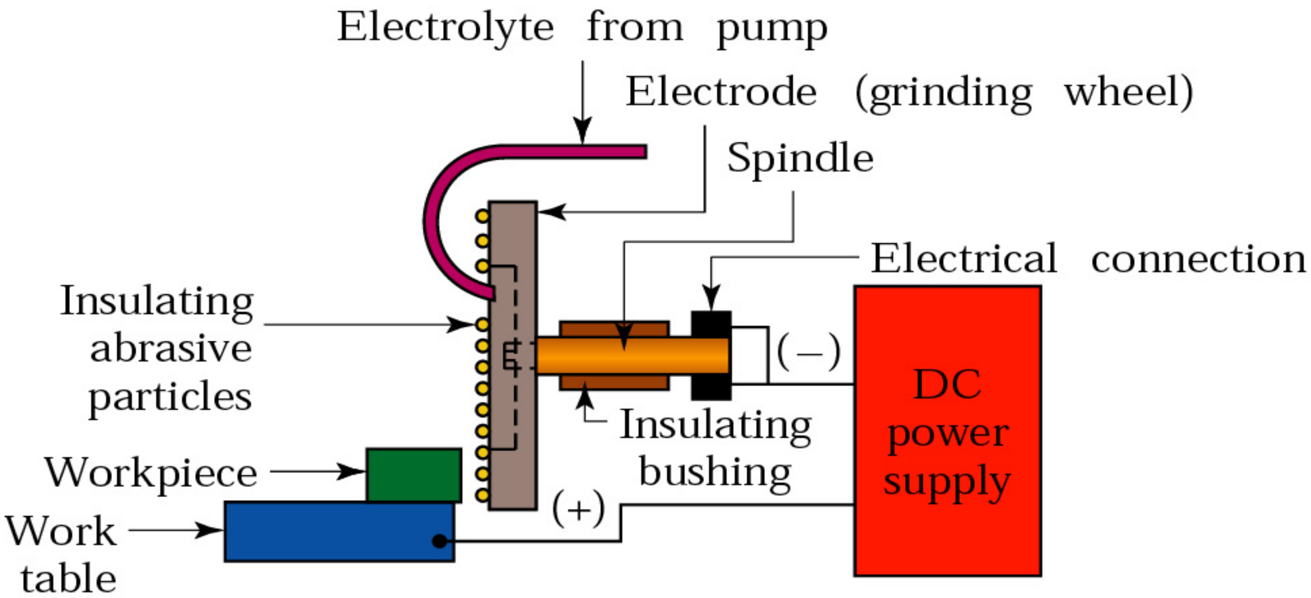
- Advantages of ECM
  - The components are not subject to either thermal or mechanical stress
  - There is no tool wear during electrochemical machining
  - Complex geometrical shapes can be machined repeatedly and accurately
  - During drilling, deep holes can be made or several holes at once.
  - Surface finishes of 25 μ in. can be achieved during ECM
- Disadvantages of ECM
  - The cost of the equipment is very high.
  - Rigid fixture is required to withstand the high electrolyte flow rates.
  - Difficult in designing a proper tooling system
  - Corrosion-free materials requirement for the structure and electrolyte handling systems
  - The tool is more difficult to make since it must be insulated to maintain correct conductive paths to the work piece.
  - Spark damage may become sometimes more problematic

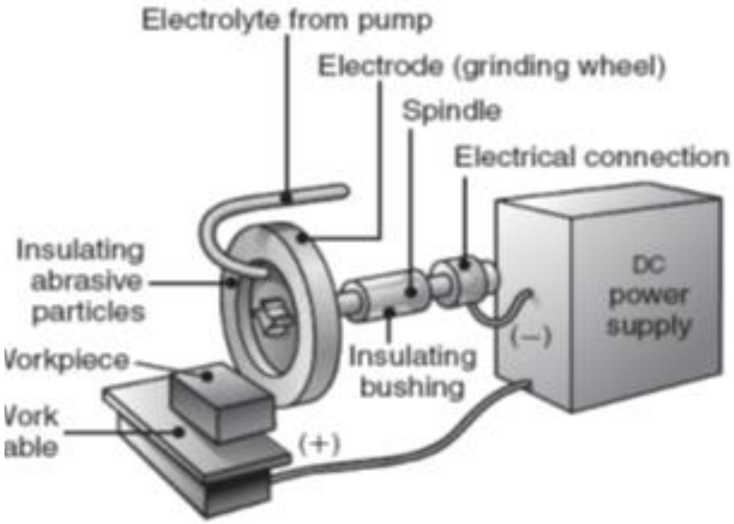
Applications of ECM

- ECM is to be applied only in specialized areas where conventional machining is not feasible. One of the main applications of ECM is in the aerospace industry to machine difficult-to-machine materials and complex shaped parts.
- Various industrial techniques have been developed on the basis of this ECM principle such as:
    - Electrochemical cutting
    - Electrochemical ECM
    - Electrochemical broaching
    - Electrochemical drilling
    - Electrochemical deburring
- Electrochemical machining is used for the manufacture of dies, press and glass-making molds, turbine and compressor blades for gas-turbine engine, the generation of passages, cavities, holes and slots in parts. ECM deburring is used for deburring of gears, hydraulic and fuel-system parts, small electronic components and engine parts.

Electrochemical Grinding (ECG)

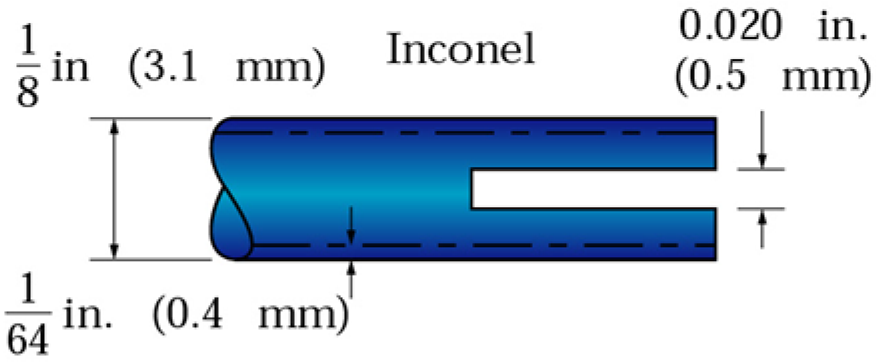
- This process employs a grinding wheel in which an insulating abrasive is set in a conducting bonded material. The D.C. power is connected to the part and the conductive bond of the grinding wheel in such a way that the latter is at negative potential with respect to the component part. Brushes are used on the grinder spindle for the supply of current into the spindle, from which it then flows to the grinding wheel. The region between the wheel and workpiece is flooded with electrolyte.





Schematic of Electrochemical Grinding Process

- When the workpiece contacts the bed of the machine, an electrolytic cell is formed, with the workpiece as anode and the body of the grinding wheel as cathode. The insulating abrasive particles in the grinding wheel protrude evenly above the wheel surface and when the workpiece is pressed into contact with these, the height of the abrasive particles above the wheel determines the effective gap between the anode and cathode. It is in this space that electrolysis actually takes place.
- A DC voltage of about 5-15 V is applied between the workpiece and the grinding wheel. Current densities ranges from 2 amp/cm^2 in grinding tungsten carbide to about 3 amp/cm^2 in grinding steel. A typical operation is shown in the following Figure.



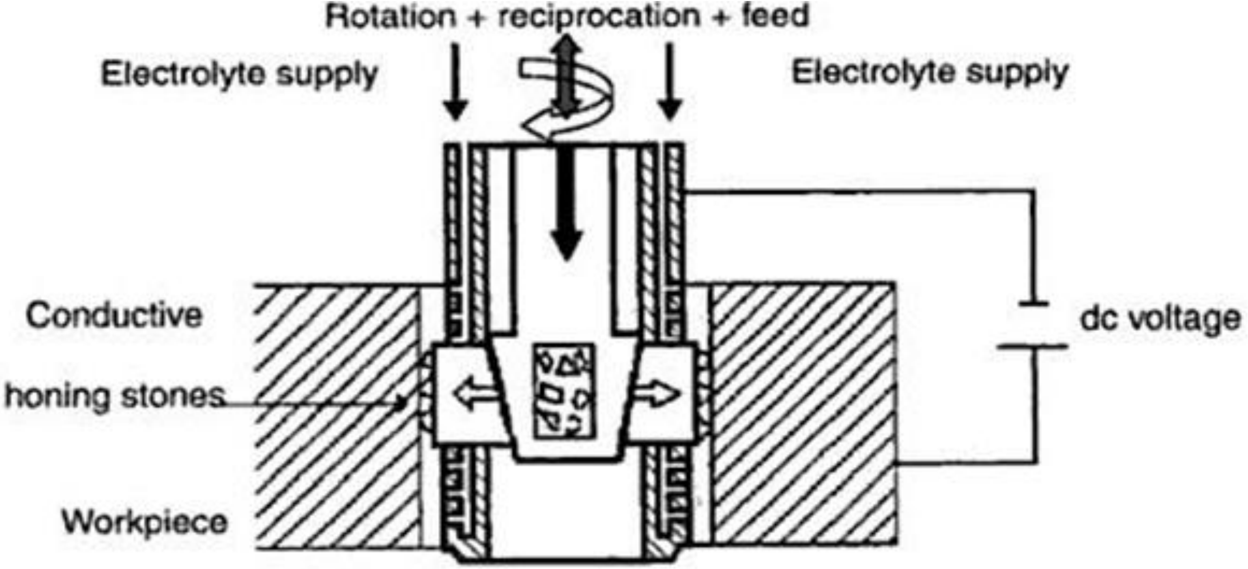
Thin slot produced on a round nickel-alloy tube by this process

Advantages and Applications of ECG

- Advantages of ECG
  - Increased material removal rate (MRR)
  - Reduced cost of grinding. Despite the fact that the machine required is comparatively expensive, the increased MRR and the reduced consumption of abrasive material more than compensate for the extra capital cost.
  - Reduced heating of workpiece and therefore less risk of thermal damage
  - Absence of burrs on the finished surface
  - Improved surface finish with no grinding scratches
  - Reduced pressure of the work against the wheel
- Applications of ECG
  - A wide application of electrochemical grinding is the production of tungsten carbide cutting tools.
  - ECG is also useful in the grinding of fragile parts such as hypodermic needles and thin-wall tubes.

Electrochemical Honing (ECH)

- In this process, the stock removal capabilities of ECM are combined with the accuracy capabilities of honing. The basic principles of the process regarding voltage, current, electrolyte and materials processes are the same as those described under ECM.
- The process consists of rotating and reciprocating tool inside the cylindrical components. The electrolyte is fed under pressure through holes in the tool so that at every point there is uniform flow and velocity. The gap between the tool and the workpiece is usually adjusted by the use of an expanding tool. At the beginning of the operation, the gap is approximately 1.00 mm and increases during the cycle.



Advantages and Applications of ECH

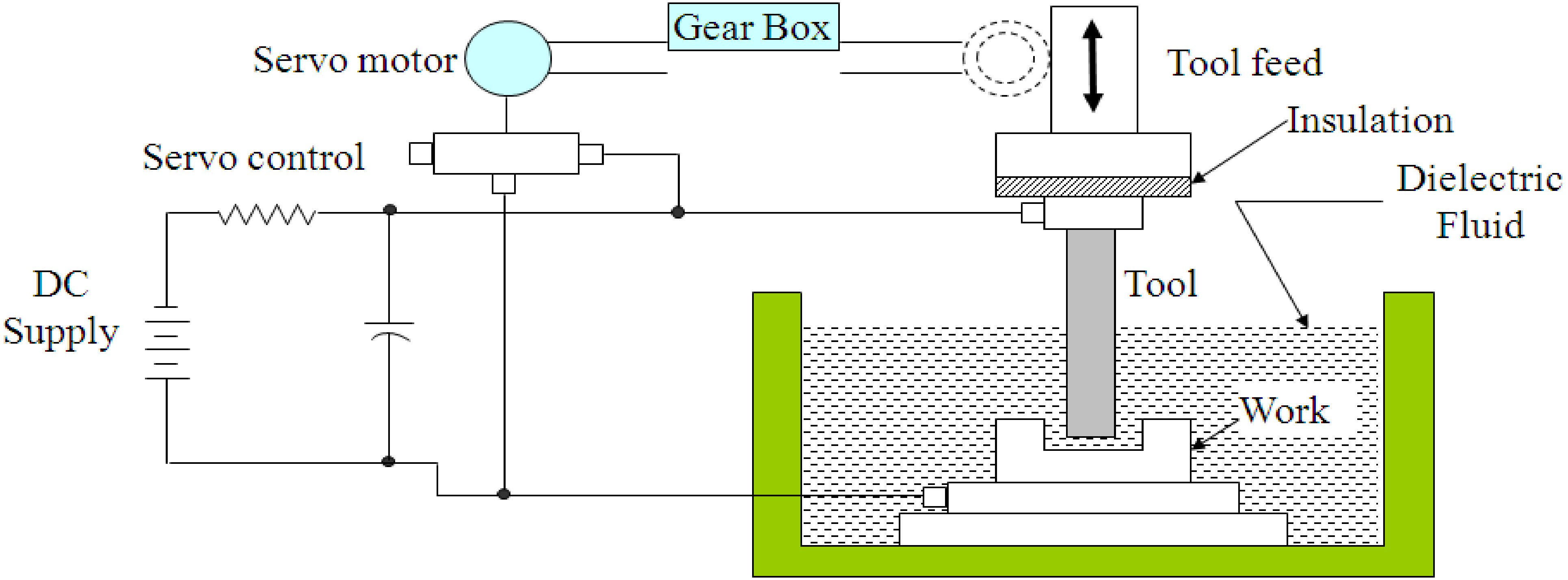
- Advantages of ECH
  - The advantages of electrochemical honing are similar to those claimed for electrolytic grinding; increased metal removal rate particularly on hard materials, burr free action, less pressure required between stones and work, reduced noise and distortion when honing thin walled tubes, cooler action leading to increased accuracy with less material damage
- Applications of ECH
  - The process is easily adaptable to cylindrical parts for truing the inside surface. The size of the cylinder that can be processed by this method is limited only by the current and electrolyte that can be supplied and distributed.
  - Any surface roughness compatible with the material being cut is duplicated over a number of component parts.

Electrical Discharge Machining (EDM)

- EDM is a machining method primarily used for hard metals or those that would be impossible to machine with traditional techniques. One critical limitation, however, is that EDM only works with materials that are electrically conductive.
- EDM is especially well-suited for cutting intricate contours or delicate cavities that would be difficult to produce with a grinder, an end mill or other cutting tools. Metals that can be machined with EDM include Hardened tool-steel, Titanium, Carbide, Inconel and Kovar.
- EDM is sometimes called spark machining because it removes metal by producing a rapid series of repetitive electrical discharges. These electrical discharges are passed between an electrode and the piece of metal being machined. The small amount of material that is removed from the workpiece is flushed away with a continuously flowing fluid. The repetitive discharges create a set of successively deeper craters in the work piece until the final shape is produced. There are two primary EDM methods: (i) Sinker or Ram or Conventional EDM and (ii) Wire EDM

- Sinker or Ram EDM
  - Sinker EDM, also called Ram or Conventional EDM, uses an electrically charged electrode to burn a specific shape into a metal component. It sinks shape from the electrode part into the oil immersed work piece, not cutting all the way through the piece.
  - The electrode discharges pulsed electrical sparks that jump to the work piece and tear out small particles. The materials most commonly used for the electrode are graphite, brass or copper tungsten. Graphite is used because of its machining capabilities and wearability, and copper for its fine finish requirements.
  - Through sinker EDM, parts can be formed out of even the most rigid materials and formed into very complex shapes. However, there are also some materials that cannot be cut with sinker EDM because they are not electrically conductive. These materials include hard and soft ferrite materials and epoxy-rich bonded magnetic materials.

- Sinker EDM is used when parts need tight tolerances or when a tight corner radius is required. Sinker EDM is a versatile process, allowing for a variety of sized parts from those that can fit in the palm of a hand to parts that weigh over 1,000 pounds, and everything in between. Production dies and molds are often made through the sinker EDM process for these reasons as well.



- This process is used to produced the different parts for the following industries.
  - Medical and Surgical Industries
  - Commercial and Military Industries
  - Aerospace and Missile Industries
  - Fiber Optics Industry
  - Hydraulic Sleeves and Slides
  - Dental Instruments

Aircraft Manifolds

Parts for Dental Industry

Military Parts

Aerospace Parts

Fiber Optic Components

Tool Material

- The selection of the tool material depends upon many factors such as:
    - It should have low erosion rate or good work to tool wear ratio
    - It should be electrically conductive
    - It should have good machinability
    - It should have low electrical resistance
    - It should have high melting point
    - It should have high electron emission.
- One of the major draw back of EDM is the wear ratio of the tool. The wear ratio may be defined as:

$$\boxed{\text{Wear ratio} = \left(\frac{\text{Loss of tool material (volumetric) in a given time}}{\text{Volume of matel removed from the work in the same time}}\right)}$$

- The less the wear ratio, the better it is
    - Wear ratio for brass electrode is 1:1.
    - For most other metallic electrodes, it is about 3:1 or 4:1.
    - With graphite (with the highest melting point, 3500^{o}C), the wear ratio may be range from 5:1 upto 50:1.
- The usual choices for tool (electrode) materials are: Copper, brass, alloys of zinc and tin, hardened plain carbon steel, copper tungsten, silver tungsten, tungsten carbide, copper graphite, and graphite. The various factors affecting the choice of electrode material are:
    - Machining applications,
    - Material being machined,
    - Availability,
    - Cost and the practical limitations inherent in processing the electrodes to the desired shape.

Tool Wear

- During the EDM process the tool also gets eroded which is undesirable no doubt but unavoidable too. However the wear of the cathode is much less than that of the anode.
- Reasons for more wear on the anode :
    - The positive ions of the dielectric fluid strike the cathode whereas the electrons to the anode. The mass of electrons is much less than that of the ions but it moves with much greater velocity than the ions do. So the cathode gets eroded much less than the anode.
    - Due to the spark a compressive force is created on the cathode which helps in reduction of cathode erosion.
    - The dielectric fluids are usually hydrocarbons. Due to its pyrolysis, gases evolve which produce carbon particles. These particles get deposited on the heated cathode as a thin layer which protects the tool from wear.
- Reasons for more wear on the cathode:
    - If the current density is more than the optimum value the dielectric fluid disintegrates gases form, resulting into short-circuiting. Due to this fusion of the cathode take place and hence it wears out faster.
    - In the relaxation circuit, the workpiece (anode) becomes positive and negative alternatively. On each reversal of the polarity the tool is eroded more than the workpiece.

Dielectric Fluid

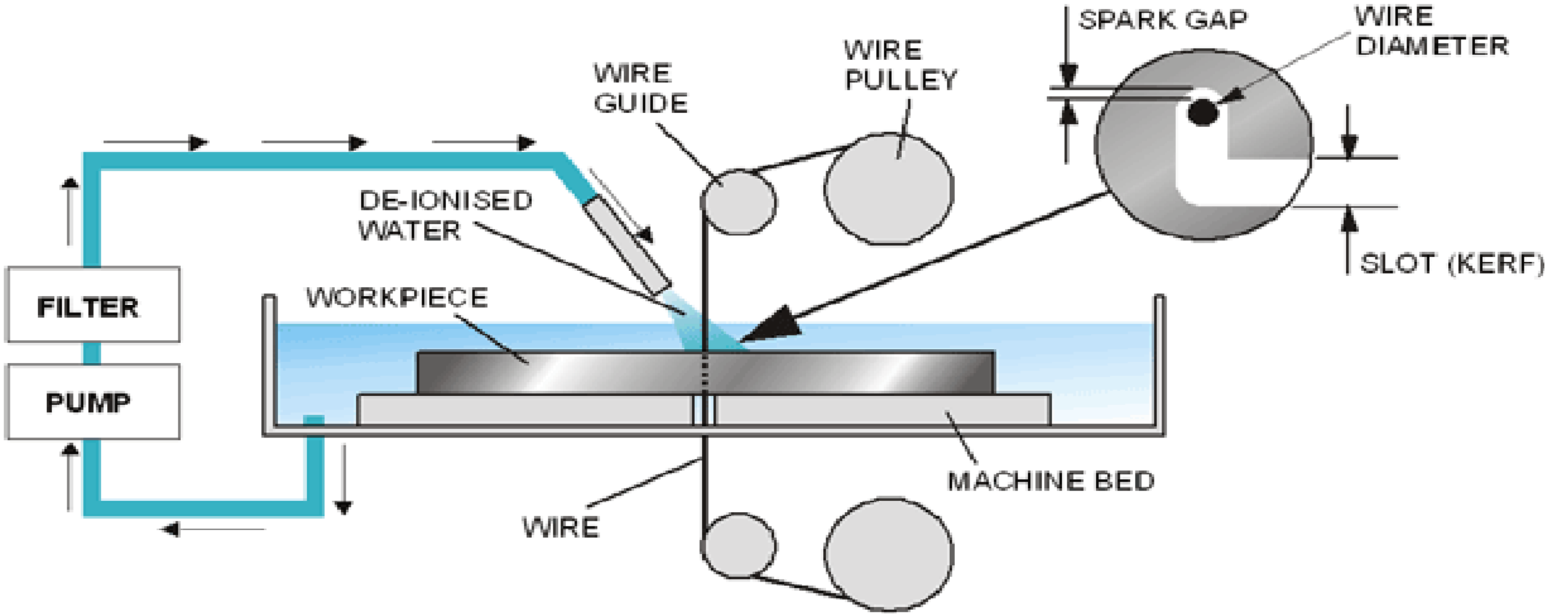
- Purpose:
  - It acts as a coolant for the workpiece and the tool
  - It acts as an insulating medium during charging operation of the condenser and provides the correct condition for efficient spark discharge and its conduction when ionized.
  - It carries away the eroded metal particles.
  - It acts as a coolant in quenching the spark and helps arcing to be prevented.
- Essential Requirements:
  - It should have an optimum viscosity.
  - It should not react with the work material, the tool or the container etc.
  - It should be inflammable
  - It should be cheap and easily available
  - It should not evolve gases during operation
  - It should not evolve toxic vapors during operation
  - It must be a hydrocarbon.
- The various dielectric fluids are: kerosene, transformer oil, white spirit, oil etc. Some conducting powers such as aluminium or fine and light density graphite if added to the dielectric fluid, the metal removal rate increases.

Advantages, Disadvantages and Applications of EDM

- Advantages of EDM
  - Complex shapes can be produced while it is difficult to be machined by conventional Machining
  - Extremely hard material can be cut with tight tolerance
  - Good surface finish can be obtained
  - The part can be machined without perceivable distortion, because there is no direct contact between tool and work piece
- Disadvantages of EDM
  - High power consumption
  - The removal rate of material is very slow
  - Due to electrode wear, it is difficult to reproduce sharp corners on the workpiece
  - Excessive tool wear occurs during machining
- Applications of EDM
  - This process is used for shaping alloy steel and tungsten carbide dies, used for molding, forging, extrusion, wire drawing or suitable mold cavities, press tools and to give any intricate shape or profile.
  - This process is very useful for making hole of nozzles, other holes as small as 0.1 mm, shapes, profiles and embossing, engraving operations on harder materials.

Wire Electrical Discharge Machining

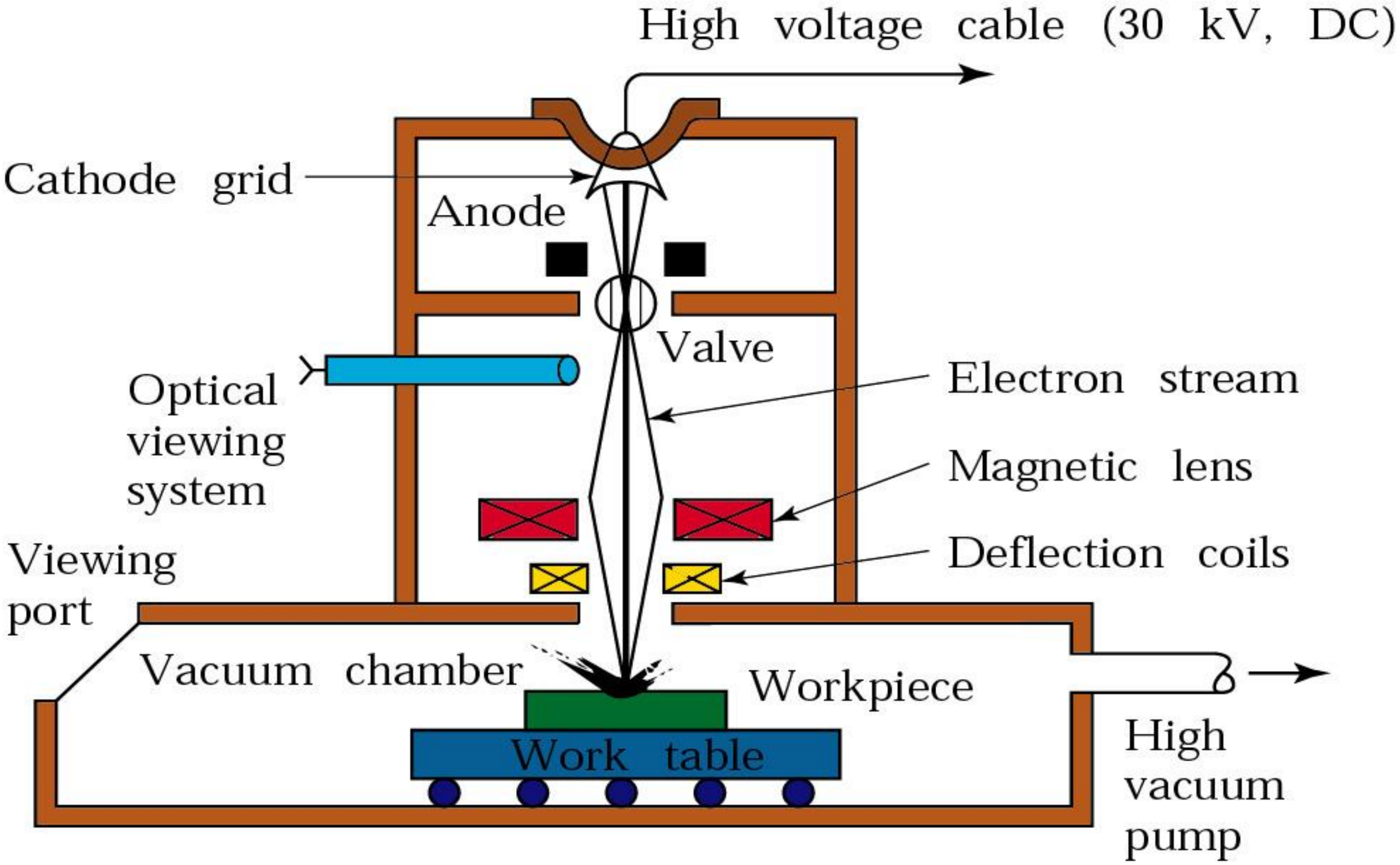
- The wire-cut EDM uses a very thin wire 0.02 to 0.3 mm in diameter as an electrode and machines a workpiece with electrical discharge like a band saw by moving either the workpiece or wire. Erosion of the metal utilizing the phenomenon of spark discharge is the very same as in conventional EDM. The prominent feature of a moving wire is that a complicated cutout can be easily machined without using a forming electrode.



- Wire-cut EDM machine basically consists of a machine proper composed of a workpiece contour movement control unit (NC tension; a machining power supply which applies electrical energy to the wire electrode; and a unit or copying unit), workpiece mounting table and wire driver section for accurately moving the wire at constant tension; a machine power supply which applies electrical energy to the wire electrode; and a unit which supplies a dielectric fluid (distilled water) with constant specific resistance. The various features of wire cut EDM process are:
  - Forming electrode adapted to product shape is not required
  - Electrode wear is negligible
  - Machined surfaces are smooth
  - Geometrical and dimensional tolerances are tight
  - Relative tolerance between punch and die is extremely high and die life is extended
  - Straight holes can be produced to close tolerance
  - Machining is done without requiring any skill.

Electron Beam Machining (EBM)

- In EBM, first the electron is generated by the cathode and an annular biased grid does not allows the electron to diverge.
- From the annular bias grid, the electron produced by the cathode is attracted towards the anode and gradually its velocity increases. As the electron beam leaves the anode section, its velocity reaches to half of the velocity of the light.
- After that, it passes to the series of magnetic lenses. The magnetic lenses allows only convergent beam to pass through it and captures the divergent beam from the fringes. And then a high quality electron beam is made to pass through the electromagnetic lens and deflector coils.
- The electromagnetic lens focuses the electron beam to the desired spot on the workpiece. The deflector carefully guides the beam to the desired locations and improves the shape hole.
- The stream of high energy electrons posses a very high energy density (104 kW/mm^2) and when this narrow stream strikes the workpiece (by impact), the kinetic energy of the electrons is converted to powerful heat energy which is quite sufficient to melt and vaporize any material.



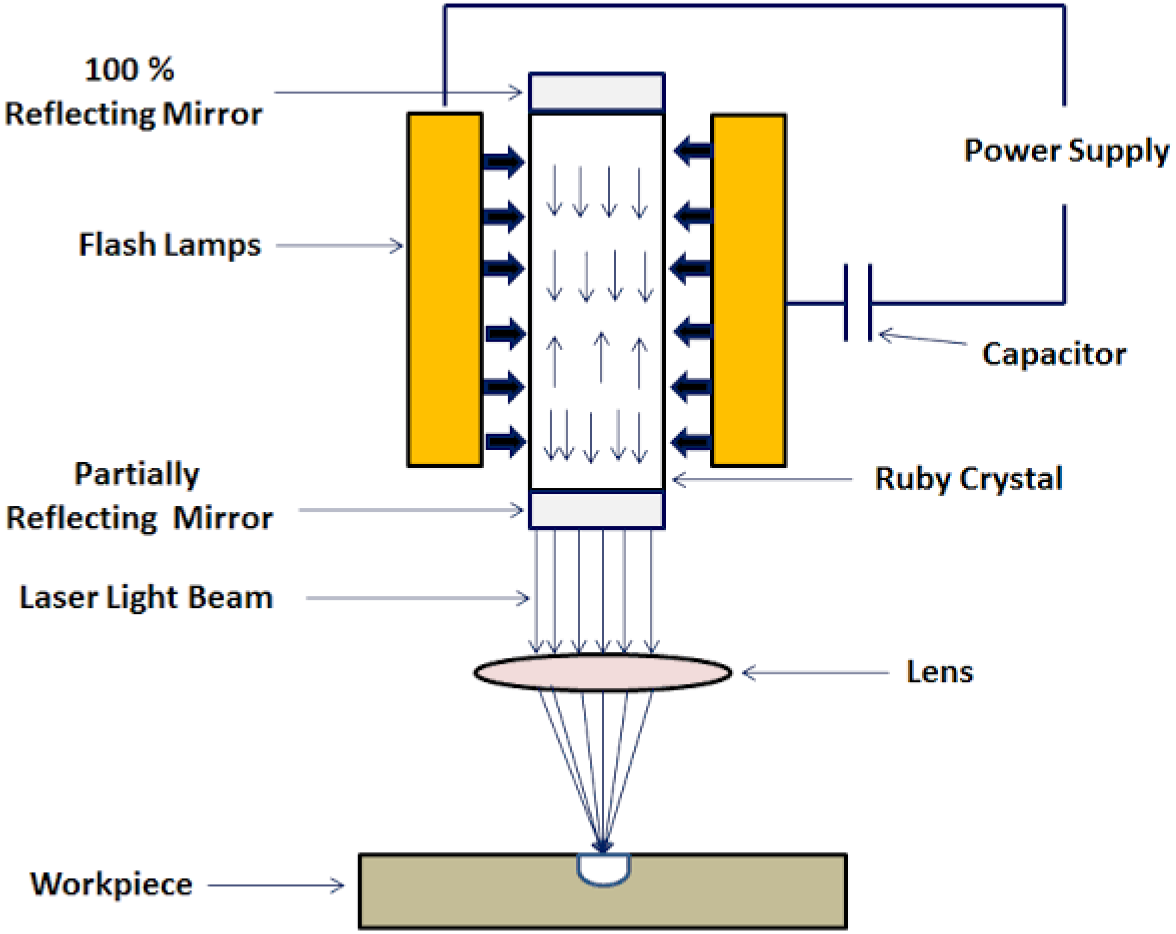
Schematic illustration of the electron-beam machining process.

- Characteristics of EBM
  - The Electron Beam machine is operated in pulse mode and this is achieved by the biasing annular biased grid.
  - The beam current can be as low as 200 µamp to 1 amp.
  - The pulse duration achieved in the EBM machine is 50 µs to 15 ms.
  - The energy possessed by the pulse is 100 j/pulse.
  - It utilizes voltage in the range of 150 kV to 200 kV. And this voltage is used to accelerate Electrons to about 200,000km/s.
- Advantages of EBM
  - Very hard, heat resistant materials could be machined or welded easily
  - No physical or metallurgical damage results in the workpiece.
  - Close dimensional tolerance could be achieved since there is no cutting tool wear.
  - In electron beam welding there is virtually no contamination and close control of penetration is possible.
  - Holes as small as 0.002 mm diameter could be drilled.

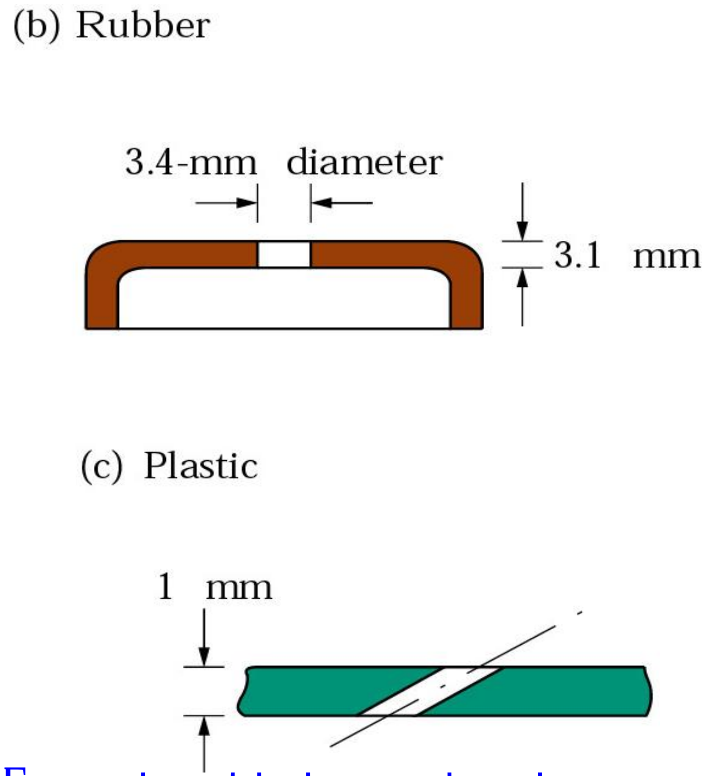
- Disadvantages of EBM
  - High equipment cost.
  - Low metal removal rate.
  - High skilled operator is required.
  - High power consumption.
  - Not applicable to produce perfectly cylindrical deep holes.
- Applications of EBM
  - It is used for drilling synthetic jewels in the watch industry.
  - Holes as small as 0.002 mm diameter can be produced in hard synthetic sapphires.
  - Electron beam can be suitably used for welding small pieces of highly reactive and refractory metals.
  - For making fine gas orifices in space nuclear reactors and turbine blades for supersonic aero engines, it is used
  - Wire drawing dies, flow orifices could be produced by this process.
  - Fine copper wire can be welded to in transistors.

Laser Beam Machining (LBM)

- The full form of LASER is Light Amplification by Stimulated Emission of Radiation.
- When electrons of an atom are provided an external energy source, they absorbs energy from the external source. By absorbing the energy these electrons jump from their original energy level to higher energy level. But this is not stable condition of atoms, so this electron emits absorbed energy in the form of photons of light and come back to its original state. This emission of photons by electrons is called spontaneous emission.
- The atom will emit double energy if it is already at higher energy level and it again absorbs energy.
- The energy emitted by atom will have same frequency and wavelengths as that of stimulating source. This is the fundamental principle on which laser works.
- When a laser material is placed under some energy source, it absorbs energy to some extent and release it when it reaches its absorbing limit. Thus the highly amplified light produced is called laser.
- Laser machining process works on the basic principle of laser. In this machining process, a laser beam is used which is a monochromatic high intense light which can cut any metal and non-metal.
- Laser machining can be used to cut and remove material from even the hardest material present which is diamond.



Schematic illustration of the LBM process

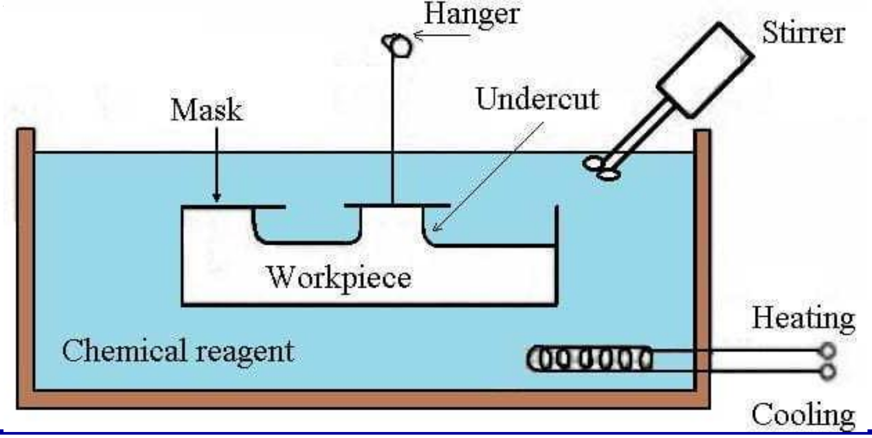


Examples of holes produced in nonmetallic parts by LBM.

- Advantages of Laser Beam Machining
  - It can be used to cut any material.
  - No tool cost because no physical tool is required
  - No delamination is caused as there is no physical contact with the workpiece.
  - It can be easily automated and is very flexible.
  - Complex shapes of different sizes can be machined as laser can be moved in any path.
  - It gives very good surface finish.
  - Micro holes can be drilled in workpiece with high accuracy.
- Disadvantages of Laser Beam Machining
  - Very high capital and maintenance cost.
  - It cannot be used to produce blind hole.
  - It can lead to safety hazards.
- Applications of LBM
  - Used for making very small holes (holes in rubber baby bottle nipples).
  - Can be used for mass micro-machining production.
  - Can also be used for selective heat treating of materials
  - It is also sometimes used for dynamic balancing of rotating parts.
  - It is very useful for producing very fine and minute holes etc.

Chemical Machining (CHM)

- Chemical machining is the material removal process for the production of desired shapes and dimensions. It is done by selective or overall removal of material by a controlled chemical attack with acids or alkalies.
- The metal is slowly converted into metallic salt by chemical reaction and is finally removed in this form. Areas from where the material is not to be removed are protected by an etching resistant material, known as ‘maskant or ‘resist’.
- Almost all the materials, from metals to ceramics, can be chemically machined. The component to be machined is first cleaned in trichloroethylene vapor or in a solution of mild alkaline solution at 80 to 90 °C, followed by washing in clean water.
- One of the roughest methods is to coat the component all over by spraying or dipping. This removes dust and oil. The cleaning ensures good adhesion of the coating or masking agent.
- After cleaning the component is dried and coated with the maskant material which may be cut and peel, photoresist or screen-print, type. Finally, the metal is removed by etching.



- Advantages and Disadvantages of Chemical Machining
  - The advantages are that this process does not distort the workpiece, does not produce burrs, and can easily be used on the most difficult-to-machine materials.
  - However, the process is slow, and thus it is not usually used to produce large quantities or to machine material thicker than 2 mm.
  - Some small parts are made 10 to 100 at a time on a single plate, which speeds up production.
- Application of Chemical Machining
  - CHM has been applied in a number of usages where the depth of metal removal is crucial to a few microns, and the tolerances are close.
  - The surface finish obtained in the process is in the range of 0.5 to 2 microns.
  - Besides, it removes metal from a portion of the entire surface of formed or irregularly shaped parts such as forgings, castings, extrusions or formed wrought stock.
  - One of the major applications of chemical machining is in the manufacture of burr-free, intricate stampings.