Subject : Advanced Machining Process - Elective III (ME 010 804 L02)

Semester : VIII

Course : B Tech - Mechanical Engineering

KNOWLEDGE IS POWER

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Department of Mechanical Engineering
MACE

VISION

Mentoring to ensure excellence

MISSION

- **To facilitate comprehensive and integrated development of students by providing quality education**
- **To mould disciplined and socially committed engineers capable of assuming professional leadership**

Module 1

- **Diamond turn machining (DTM)**:-Types of DTM - component of machine - components of DTM: spindle system, workpiece tool positioning system, machine support system, tool measurement system, machine control system – material removal mechanism in DTM – ductile regime machining – tools for DTM – tool geometries for single crystal diamond tools – tool setting – applications.

- **Abrasive jet micro machining (AJMM):-** machining system – masking technology – erosion mechanism – metal, photo-resist and elastomer mask – erosion behaviour – surface properties: hardness and roughness – pressurized power feed system – fluidized bed powder spray system – factors affecting in constant feeding – nozzle configuration – applications.

Module 2

- **Magnetorheological nanofinishing processes: -** Magnetorheological polishing fluid – rheological characteristics of fluid - Magnetorheological finishing (MRF) processes - Magnetorheological abrasive flow finishing processes (MRAFF) – performance analysis of MRAFF process - Magnetorheological jet finishing processes:- working principle, MR jet finishing machine, polishing performance.
- **Micro/nano finishing with flexible flow of abrasives:-** process principle and description – process technology – selection of media – effect of process parameters of performance – mechanism of material removal – process capabilities - applications.

Module 3

- **Ultrasonic micromachining (USMM):-** machine tool – Elements of USMM – abrasive slurry – workpiece – mechanism of material removal – process parameters: machine based parameters – performance characteristics: machining rate, surface roughness, accuracy and tool wear – effect of process parameters on quality characteristics – effect of process parameters on accuracy – process capabilities.

Module 4

- **Electron beam micromachining: -** mechanism of material removal in EB drilling – importance of vacuum – process parameters – effect of cutting speed, pulsed beam operation, heat affected zone, cross sectional area of a beam – theoretical aspects of electron beam – energy transfer to the work material – applications.

- **Focused Ion beam machining:-** equipment – imaging with FIB system – interaction of ion with substrate – FIB milling – gas assisted FIB processing – applications.

Module 5

- **Micro-electric discharge micromachining:-** Principle of micro –EDM **–** influence of pulse characteristics – high aspect ratio holes – heat affected zone.

- **Laser micromachining**:- Laser beam characteristics – laser material interaction – micromachining system – nanosecond, picoseconds, femtosecond pulse micromachining.

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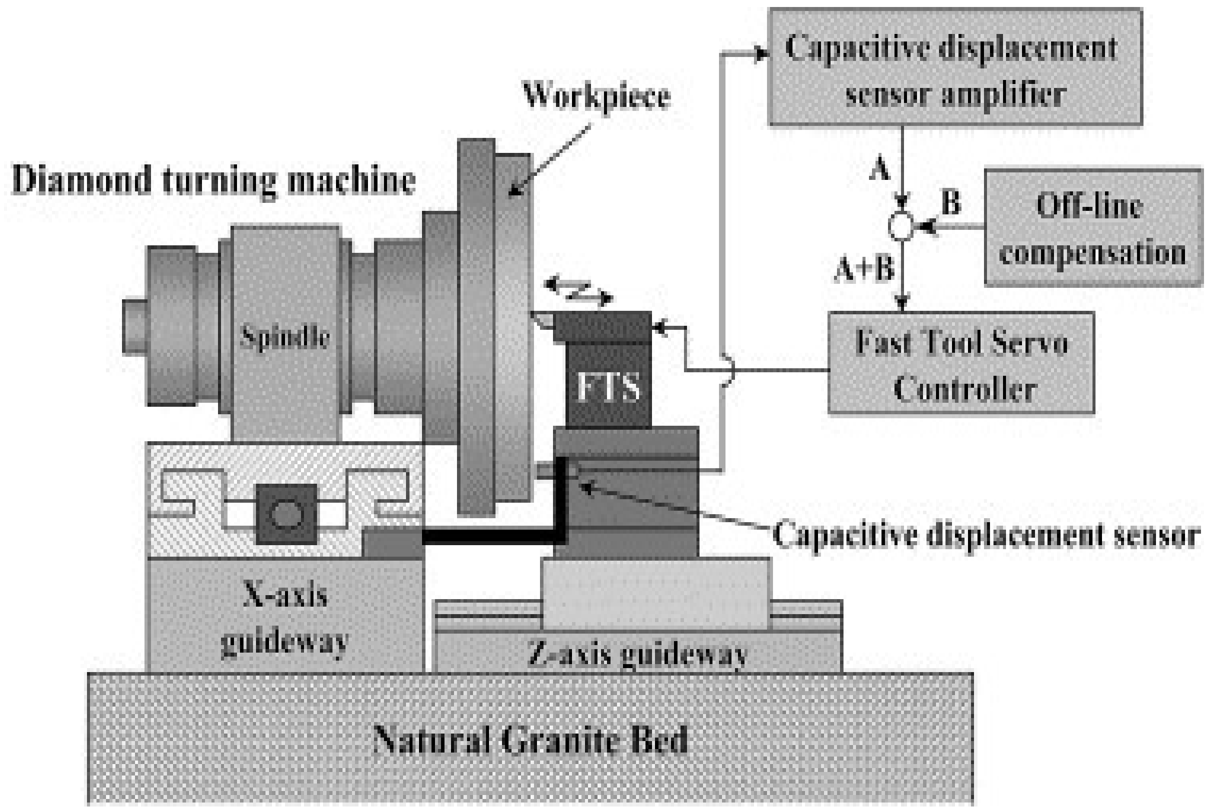
Need for Advanced Machining Processes

- Traditional machining processes
  - Material removal by mechanical means, such as chip forming, abrasion, or micro-chipping
- Advanced machining processes
  - Utilize chemical, electrical, and high-energy beams
- The following cannot be done by traditional processes:
  - Workpiece **strength and hardness** very high, >400HB
  - Workpiece material too **brittle**, glass, ceramics, heat-treated alloys
  - Workpiece too **slender and flexible**, hard to clamp
  - Part shape **complex**, long and small hole
  - Special **surface and dimensional tolerance** requirements

Module 1- Diamond Turn Machining (DTM)



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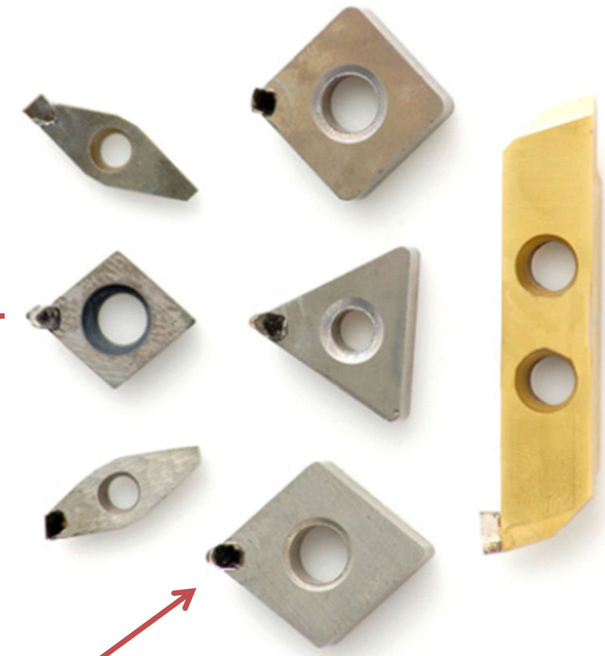
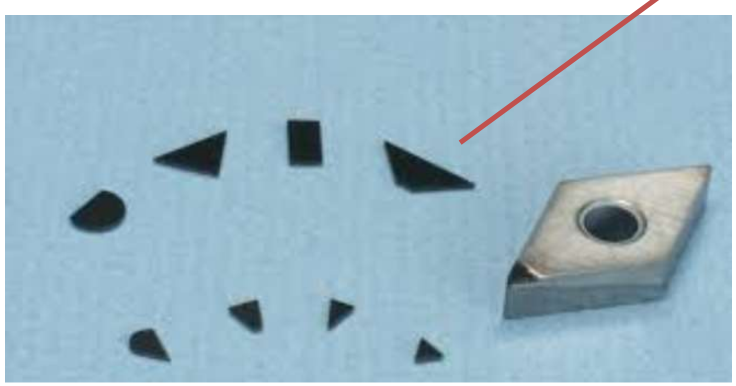
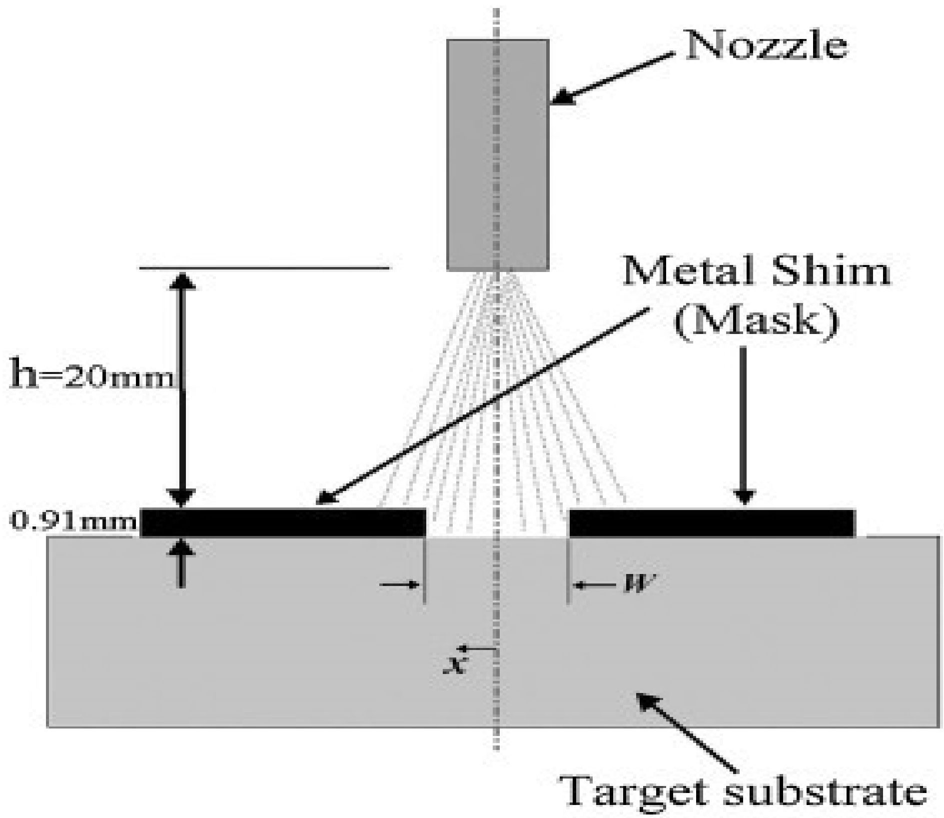
DTM Tools





Module-1 Abrasive Jet Micromachining (AJMM)



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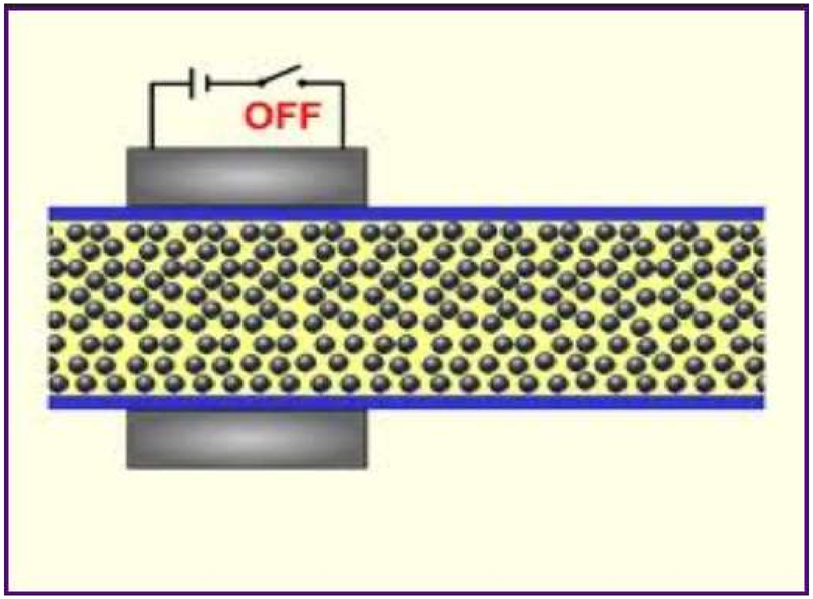
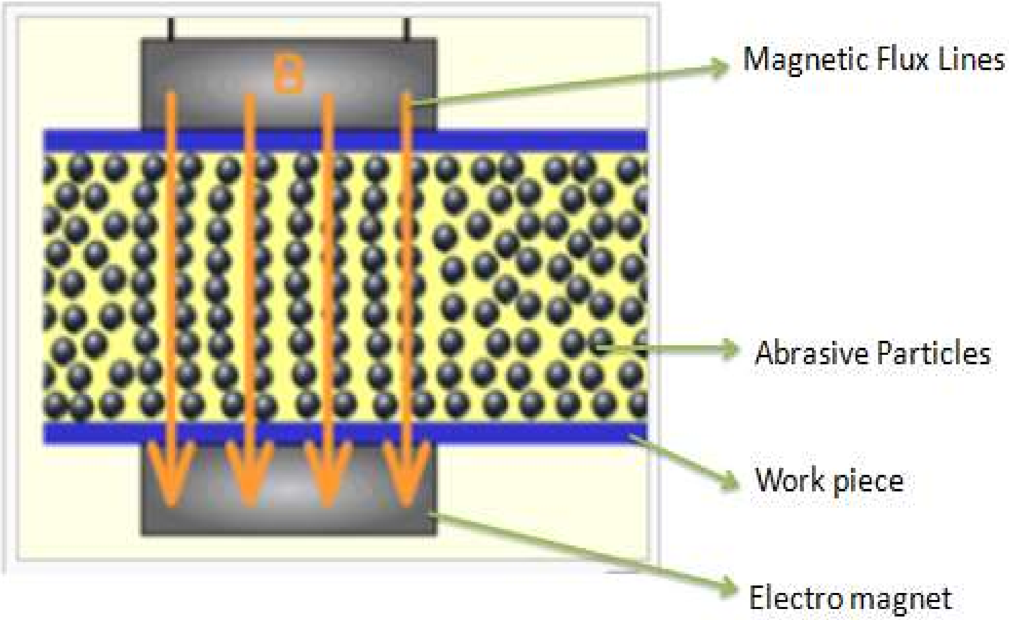
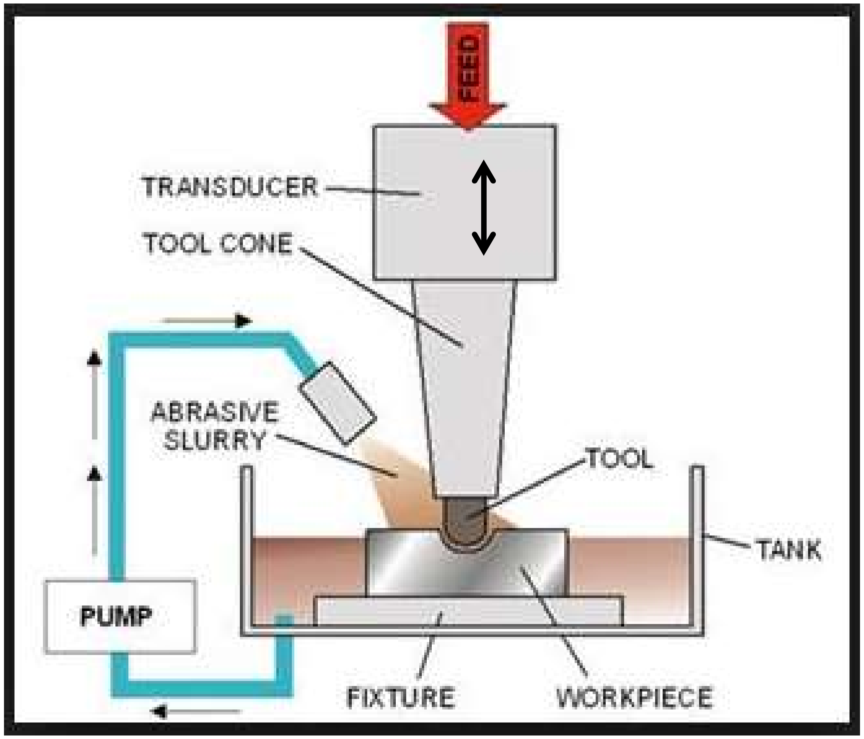
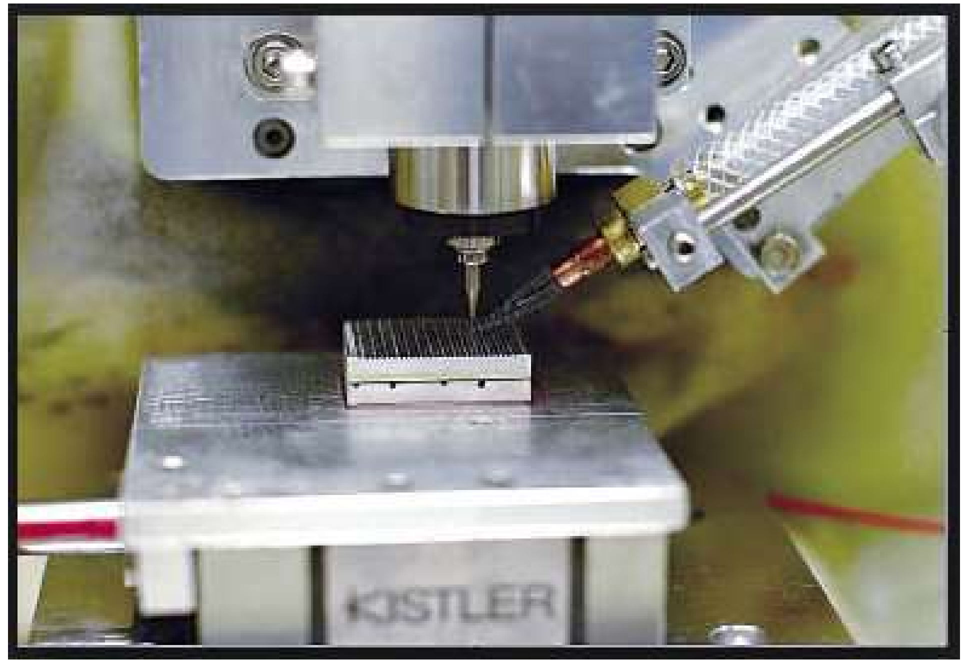
Module 2 Magnetorheological Finishing Process





Module 3 Ultra Sonic Machining (USM)





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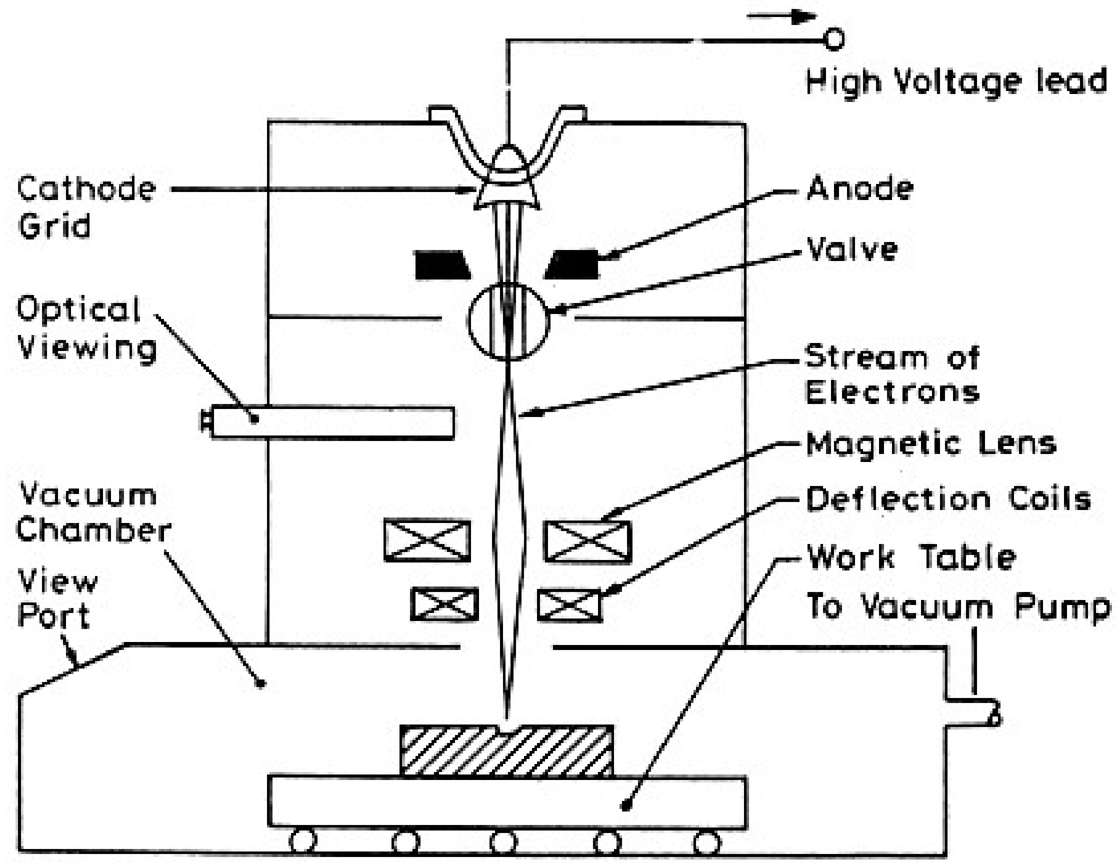
Module 4 Electron Beam Machining (EBM)



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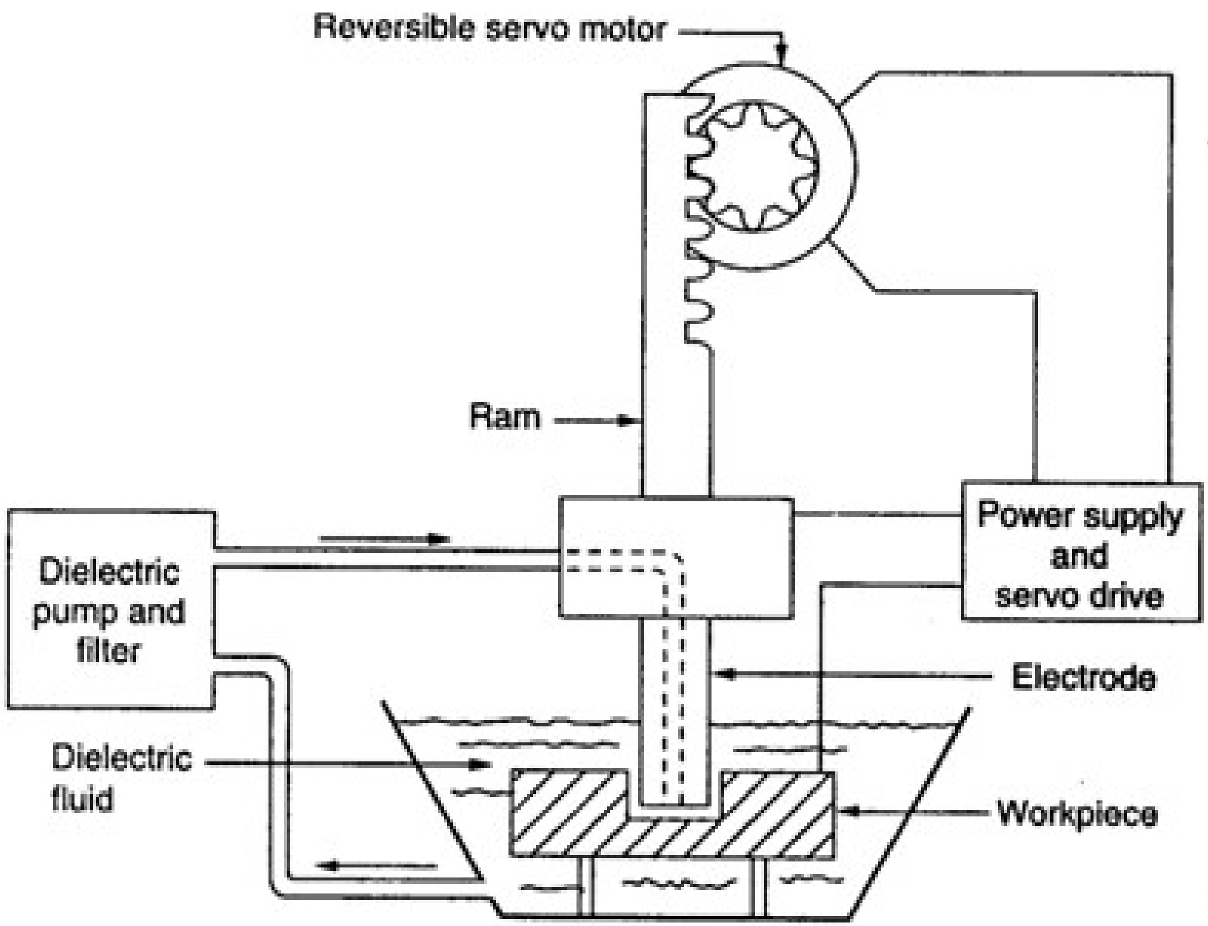
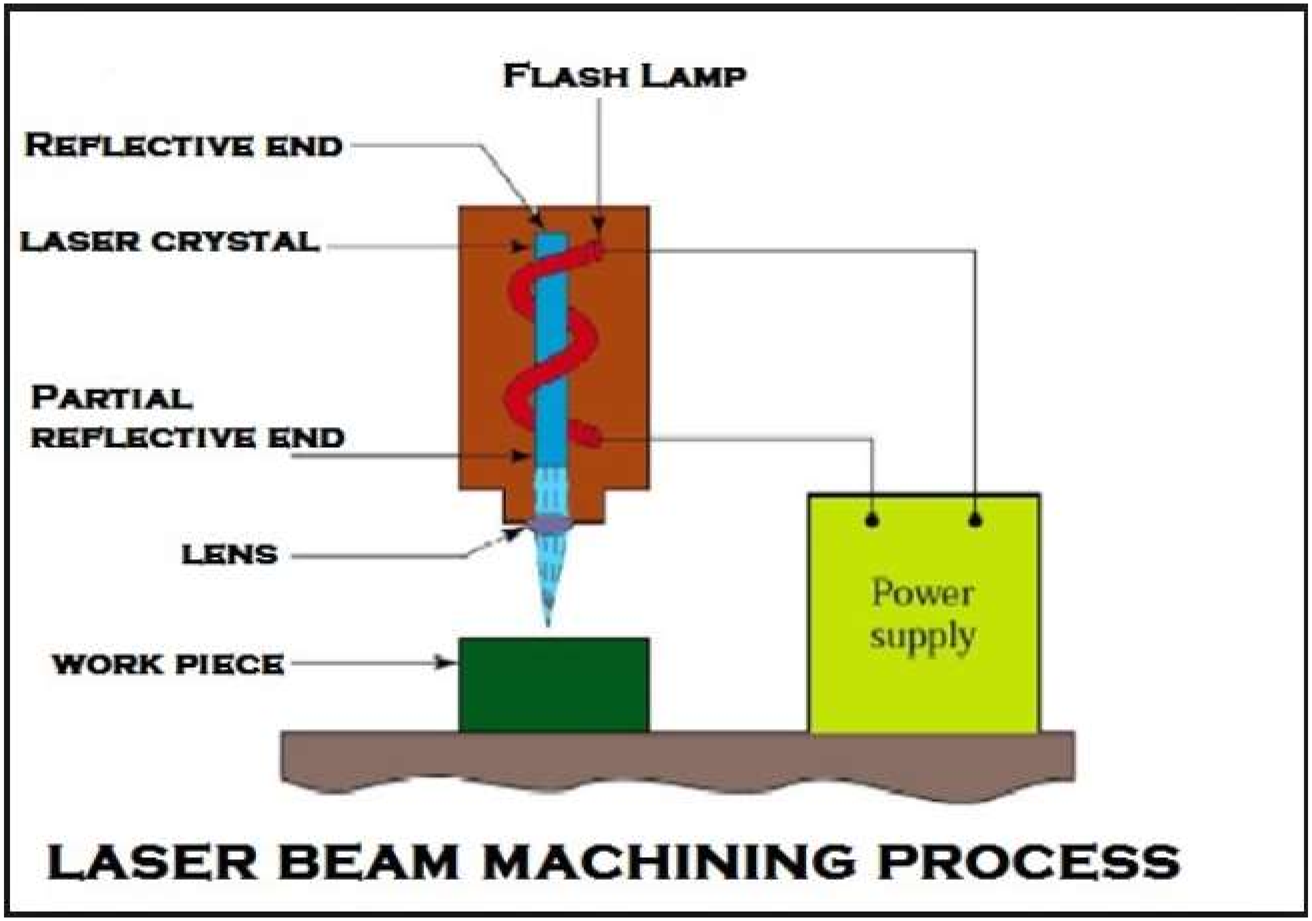
Module 5 Electric Discharge Machining (EDM)



Module 5 Laser Beam Machining (LBM)



MODULE 1

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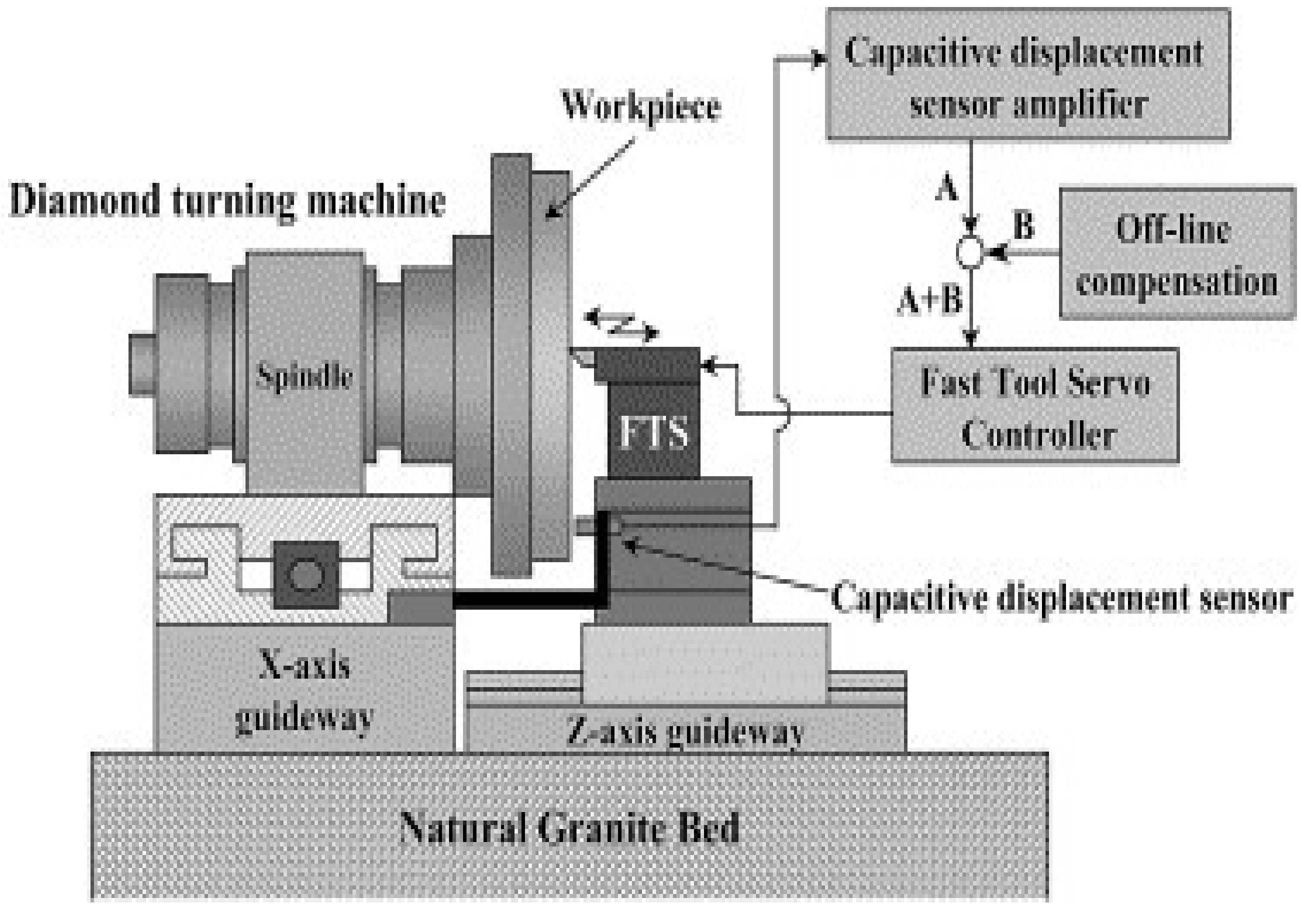
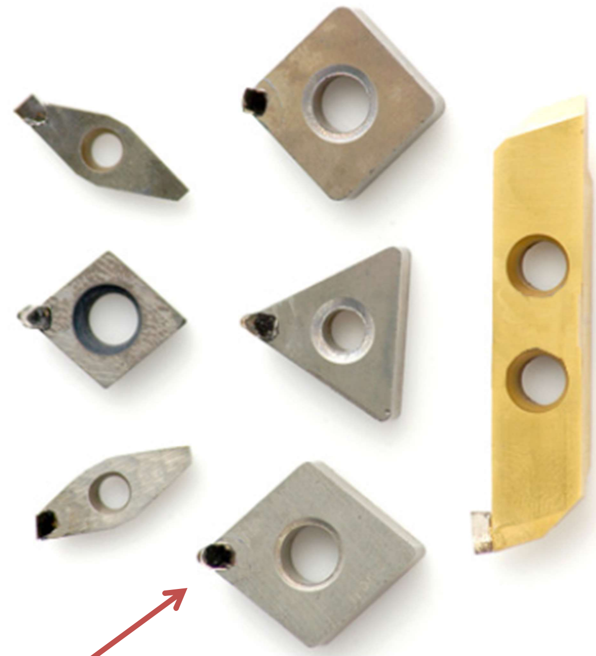
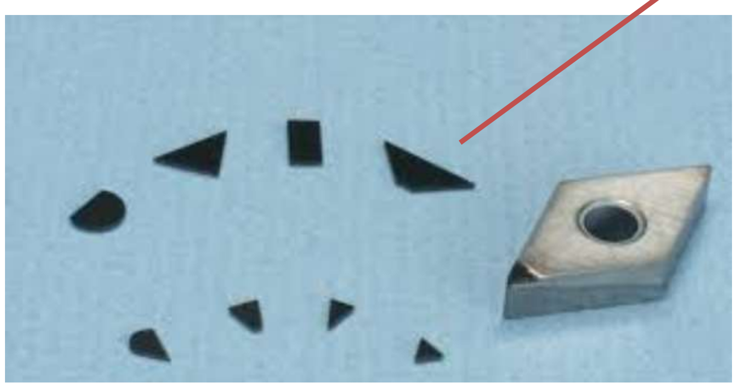
Diamond Turn Machining (DTM)



DTM Tools





Types of DTM

- Classifications are based on
  - Number of axis
    1. 2-axis
    2. 3-axis
    3. 5-axis
  - Type of coordinate system
    1. X-Z
    2. R-θ
  - Type of Machining
    1. Facing
    2. Fly cutting

2 Axis Type DTM
(Top view)

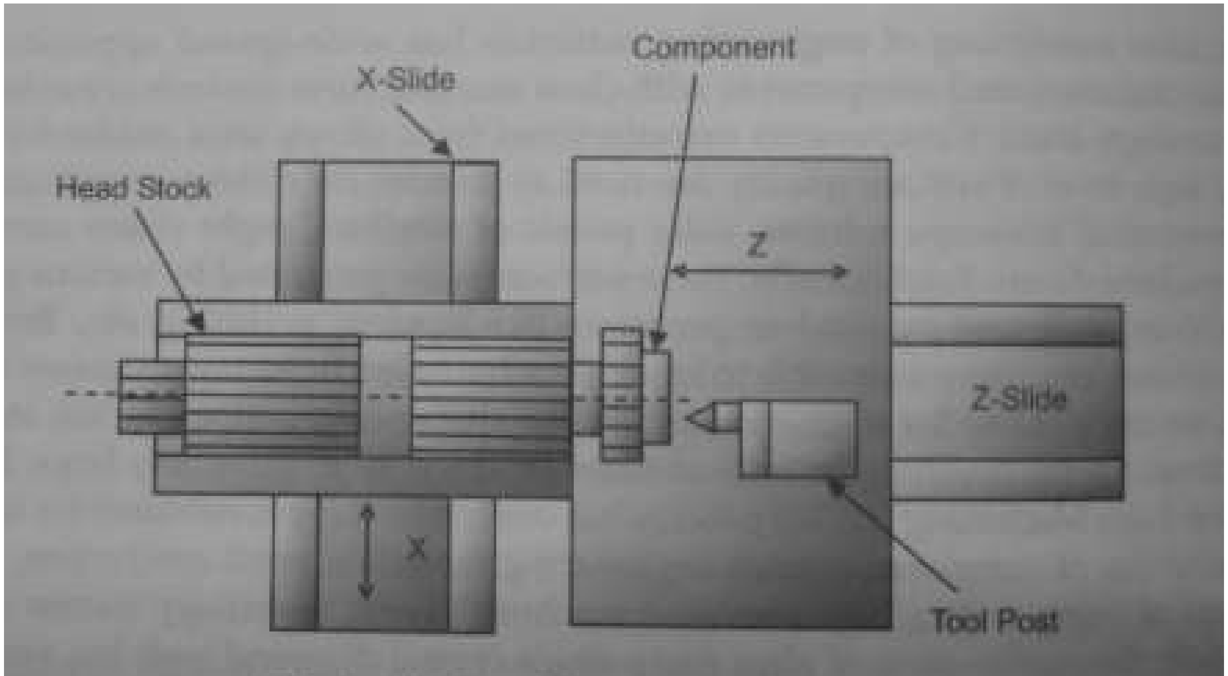


FIG. 1 X-Z Type Diamond Turn Machine

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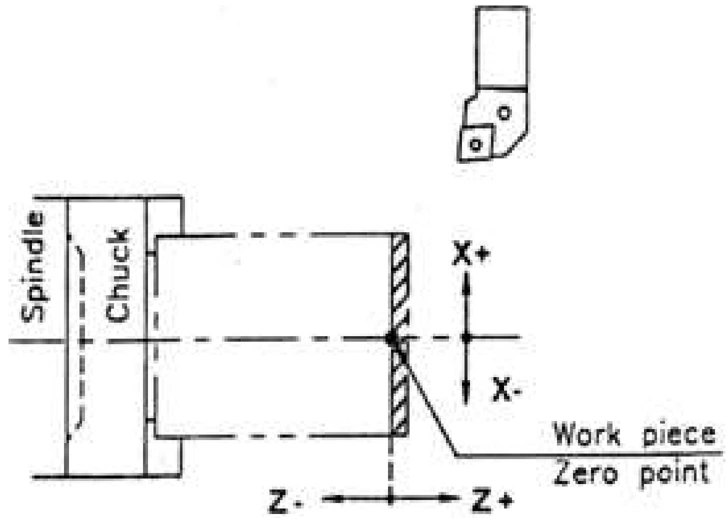
X-Z Axis



From work piece zero point

- Moving left (towards spindle) Z -ve.
- Moving right (away from spindle) Z +ve.
- Moving above spindle center line X +ve.
- Moving below spindle center line X -ve.

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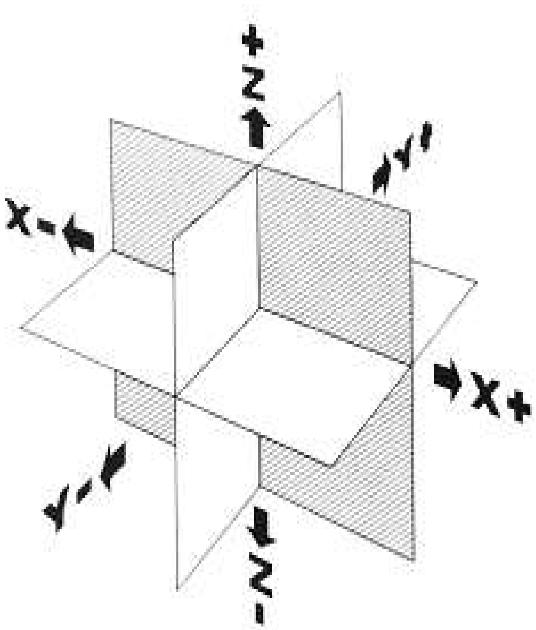
3 Axis Type DTM

- Tool moves in 3 axis (X, Y & Z)



The three-dimensional coordinate planes (axes) used in CNC.

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5 Axis Type DTM

- ❖ Additional 2 types of tool movement is possible
- ❖ Tool can swivel on its horizontal & vertical axis.

Based on type of coordinate system

1. X-Z Type

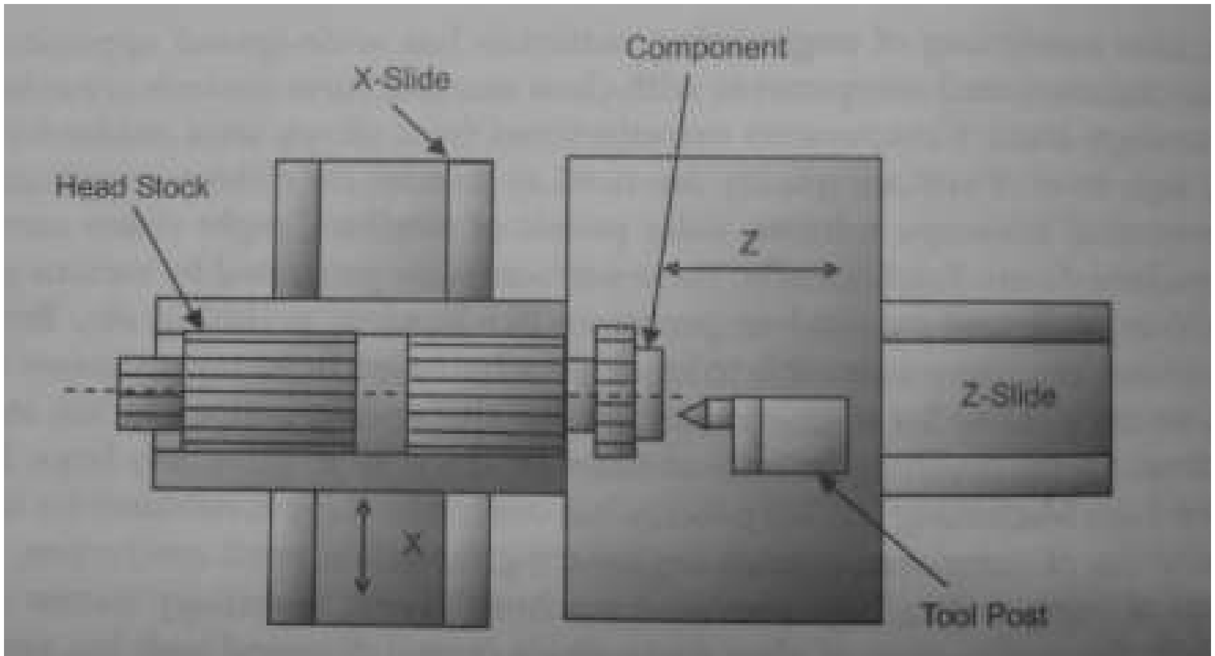
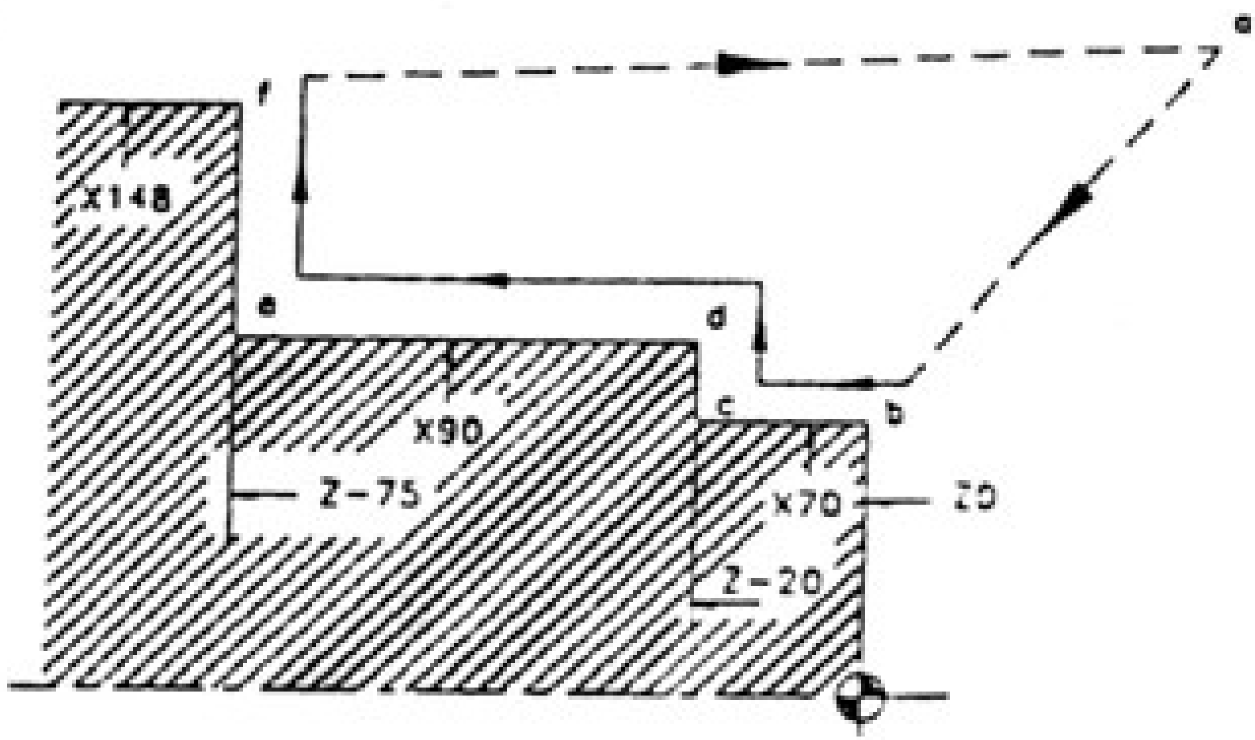


FIG. 1 X-Z Type Diamond Turn Machine

X-Z Type CNC Programming
Problem



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Solution

PROGRAM	DESCRIPTION
4567	Program Number
N1 ;	Sequence Number
MSG ("FINISHING") ;	Comment indicating operation
T04D1 ;	Selecting turret station no. 4
G96S200LIMS=3000M03 ;	Rotating spindle clock wise at 200m /min & Limiting maximum spindle speed, Coolant ON
GOO X70.0 Z1.0;	Rapid approaching upto point b
G01 Z-20.0 F0.2 ;	Cutting upto point C at feed 0.2mm/rev.
X90.0 ;	Cutting upto point d
Z-75.0 ;	Cutting upto point e.
X150.0 ;	Cutting upto point f.
GOO X200.0 Z120.0 ;	Rapid returning to point a.
M01 ;	Optional stop
M30 ;	Advising end of program

Based on type of coordinate system

2. R-θ Type

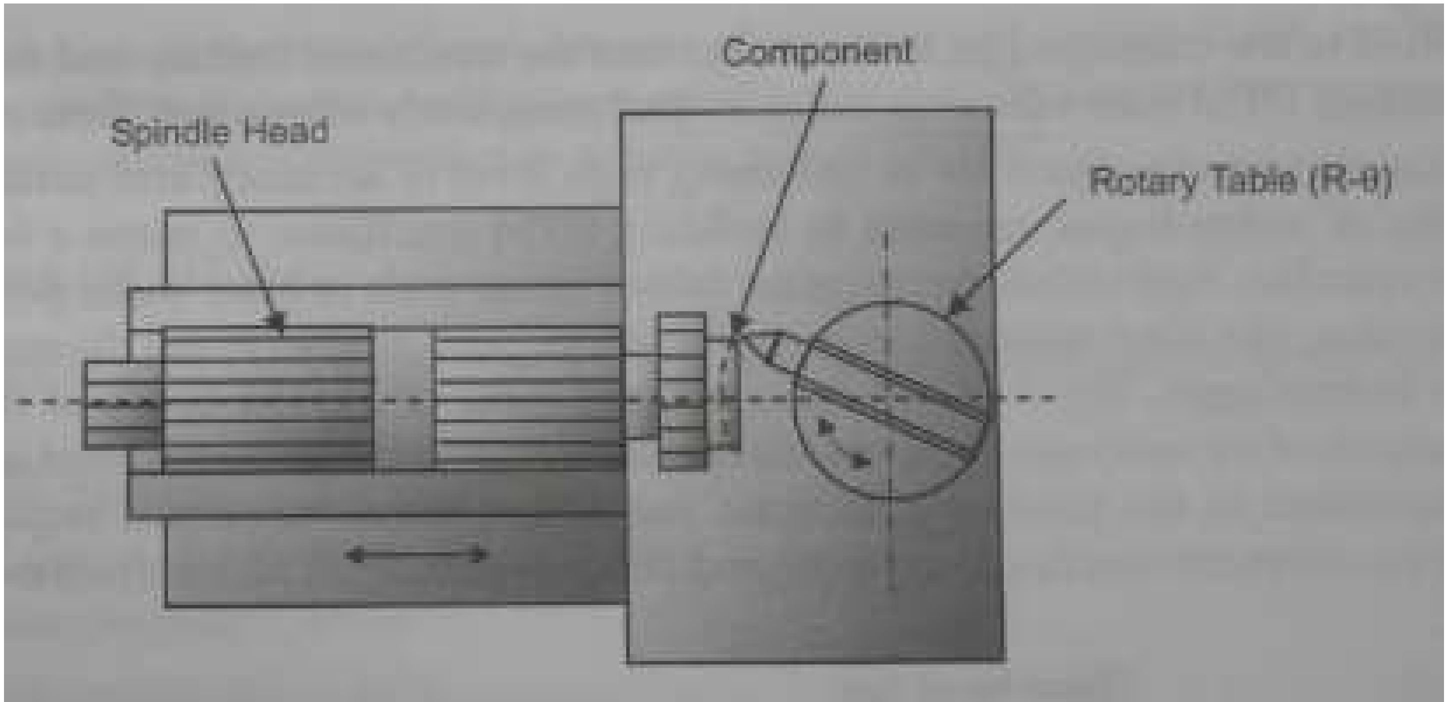

FIG. 2 R-θ Type Diamond Turn Machine

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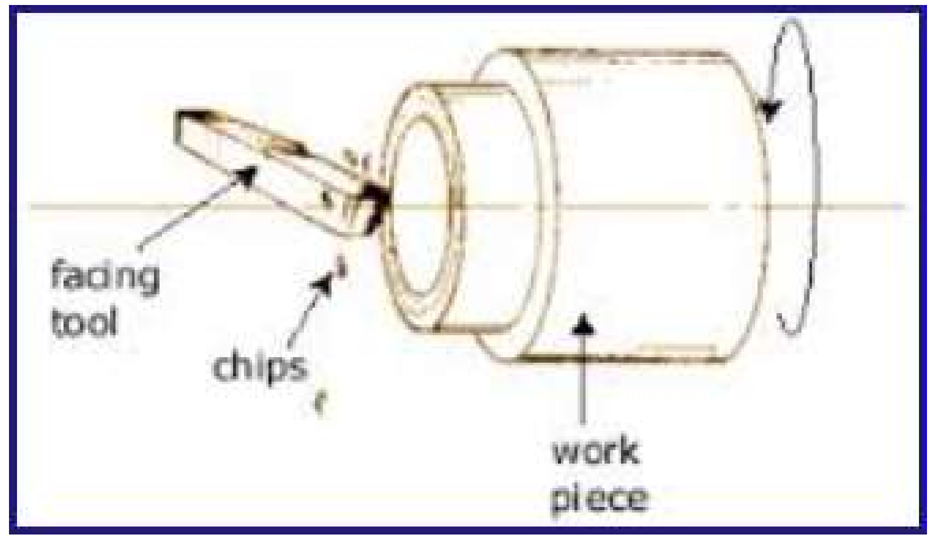
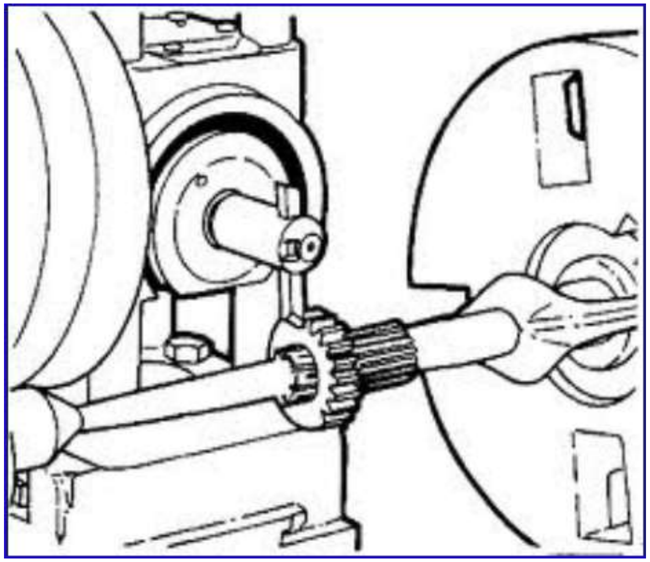
Classification based on Type of Machining

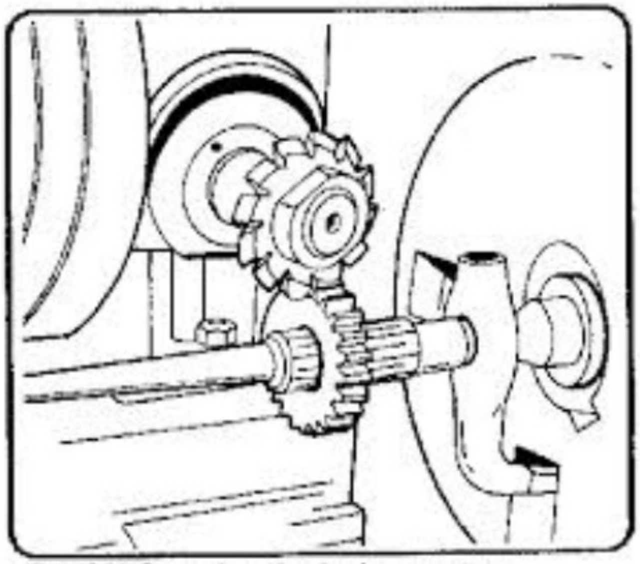
1. Facing
2. Fly cutting

Facing



Fly Cutting





Multipoint Fly Cutter

Requirements of DTM

1. Stiff & stable machine base
2. Accuracy and smoothness of spindle motion
3. Accuracy and smoothness of slide motion
4. Servo performance
5. Tool positioning accuracy
6. Vibration control
7. Temperature control
8. Tool measurement system
9. Tool quality & accuracy

Components of DTM

1. Spindle system
2. Work piece – Tool positioning system
3. Machine Support System
4. Tool Measurement System
5. Machine Control System

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Components of DTM
1. Spindle system

- Consists of

1. Spindle
2. Spindle Housing
3. Spindle Drive

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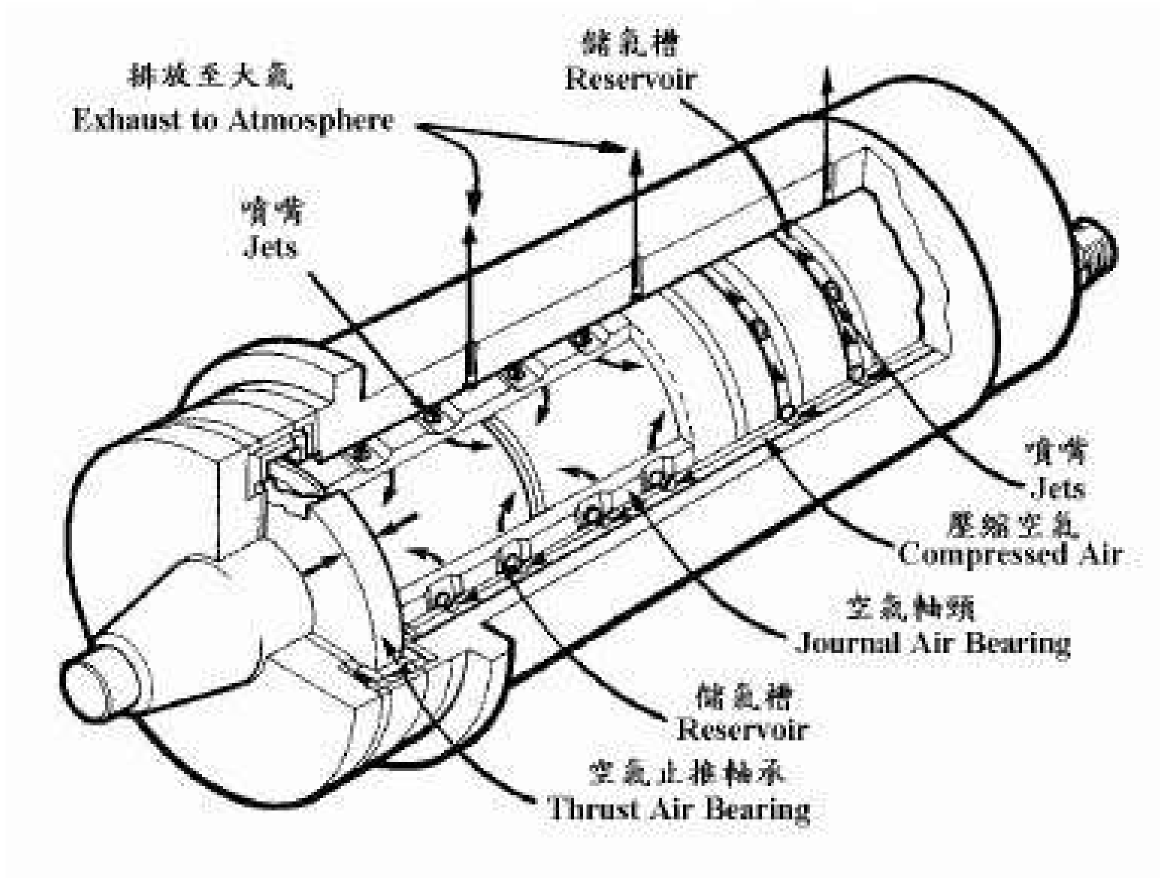
Spindle

- Heart of the DTM
- Should provide smooth rotary motion
- Should have sufficient load carrying capacity
- Aerostatic bearings / Aerostatic driving spindle are used.

Aerostatic Driving Spindle



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Aerostatic Bearing

- Typical working spindles on ultra-precision DTM's are designed with air bearing technology.
- They are stiff and hold a radial run-out error of less than 25.4 nanometer (1 micro inch) as well as handle radial loads of about 300 pounds.

Aerostatic Bearing Spindle

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Spindle Drive

- The purpose of spindle drive is to provide necessary torque for the rotation of the spindle against cutting load.
- The spindle drive system is designed to provide accuracy, smoothness of motion and adequate torque.

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Spindle Housing

- Consists of spindle and spindle drive.
- For high end machines spindle housing moves along X-axis to perform cutting action.
- In ordinary machines housing is a stationary component.
- Housing should with stand high temperature and vibrations.
- Epoxy granite is widely used to make spindle housing.

Components of DTM

2. Work piece – Tool positioning system

❖ Consists of

1. Table slide ways
2. Table drive
3. Feed back system
4. Tool post
5. Tool

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Table slide ways

- ❖ DTM has 2 slide ways – One for X axis and one for Z axis movement.

❖ Important requirements of slide ways:

1. Smooth motion to the table
2. Precise and repeatable motion
3. Adequate stiffness

Aerostatic & hydrostatic bearings are popularly used.

Table Drive

❖ Requirements of table drive:

1. Smooth & accurate drive
2. Suitable acceleration, velocity and speed characteristics

❖ Different types of table driving systems are

1. Lead screw and motor
2. Linear motors

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Feed back system

- For monitoring the work piece – tool relative position.

- Example:

1. Rotary encoder
2. Linear encoder
3. Laser interferometer

Tool Post

- Almost similar to tool posts of conventional machines.
- Will be enabled with micro height adjustment.
- Differential screw mechanism is commonly used for micro height adjustment of tool post.

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Tool

- Diamond tipped tools (inserts) are used for DTM
- Tool should be clamped properly to tool shank
- Presence of air gap between tool and shank reduces rigidity of the machining process, so it should be eliminated.

Components of DTM

3. Machine Support System

❖ Consists of

1. Machine base
2. Vibration isolator

Machine base

- Supports the DTM
- Epoxy granite is commonly used for manufacturing bases
- Thickness: 200-300 mm
- Should have excellent mechanical & thermal properties

Vibration Isolator

- DTM machines are mounted on vibration isolation system
- 3 point pneumatic damping system used will isolate the machine from vibrations and shocks
- 3 point pneumatic damping system provide automatic leveling to accommodate changes in slide position and work piece weight.

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Components of DTM
4. Tool Measurement System

- The main function of tool measurement system is to set-up the tool with respect to machine co-ordinate system.
- Parameters to be considered for a tool measurement system are

1. X and Z offset values of the cutting tool
2. Tool nose radius
3. Position of the centre of the tool nose radius
4. Tool center height
5. Waviness of the cutting edge

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Tool Measurement Systems

1. LVDT Type (Linear Variable Differential Transformer)
2. Optical Type (Machine Vision)

Components of DTM
5. Control System

- Consists of

1. Machine Control System
2. Environmental Control System

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Machine Control System

- Acts as an interface between human operator and the machine.
- A machine control system facilitates the part programming, setting of the work piece & tool and operating the machine.

❖ A machine control system monitors and controls:

1. Tool-work piece relative position
2. Spindle speed
3. Feed rate
4. Direction of machining
5. Auxiliary functions like Coolant ON/OFF, Spindle ON/OFF etc…

Environmental Control System

- For attaining accurate and optical quality surface finish, DTM requires close controls on acoustics, seismic & thermal environment.
- Environmental Control System consists of

1. Air showers for clean room to prevent dust,
2. Acoustic & vibration isolators,
3. Humidity & temperature controls for preventing corrosion and thermal expansion.

Material Removal Mechanism of DTM

Ductile Material

- Material in front of cutting tool is pushed ahead and the material slides on the shear plane.
- The shear plane offers least resistance to the flow of material which becomes a chip.
- Point defects, grain boundary defects, voids facilitates easy material removal.

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Material Removal Mechanism of DTM

Brittle Material

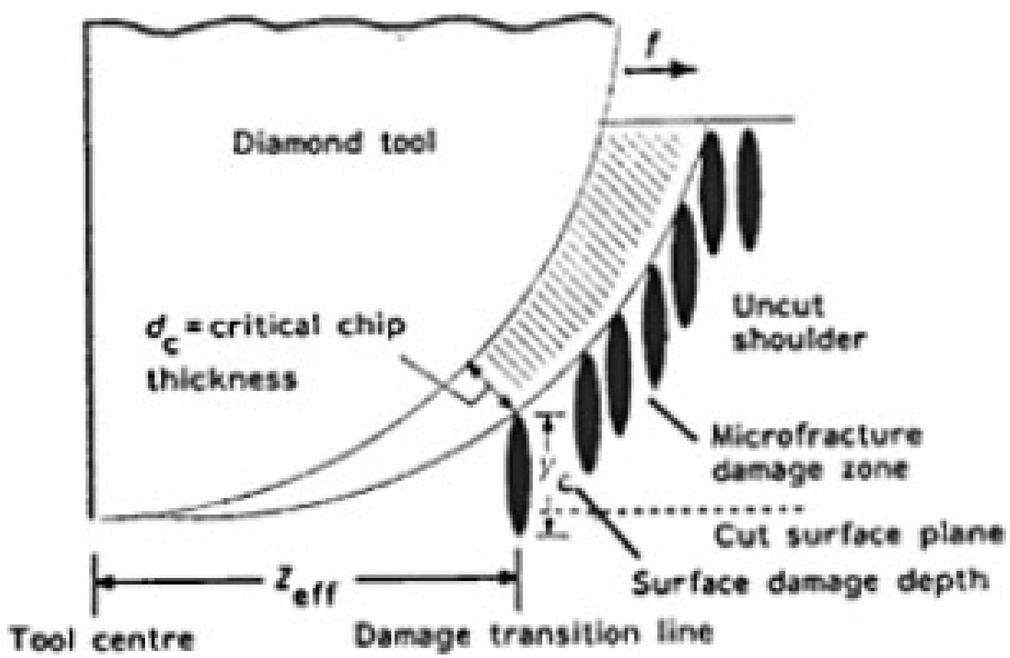
- Material is removed by crack propagation
- When the cutting load exceeds the critical value, radial and axial cracks beneath the surface are generated.
- The crack grows until it reach the surface and a chip of material is formed.

Ductile Machining vs. Brittle Machining

Ductile	Brittle
Well defined & straight edges	Jagged edges & chipped material
Controlled material removal process	Hard to control as microcracks extend below the machined surface
Final depth of cut can be predicted below the DBT depth	No direct control of the resultant depth beyond the DBT depth
Good surface finish and mechanical properties	Poor surface finish and could end in a catastrophic failure at times

Ductile Regime Machining

- Depth of damage 'yc' initiated at cutting depth 'dc' does not extend below the plane of cut surface.
- So brittle materials can be also machined like ductile materials with excellent surface finish.



Tools for DTM

- Quality of machining depends on 3 major factors

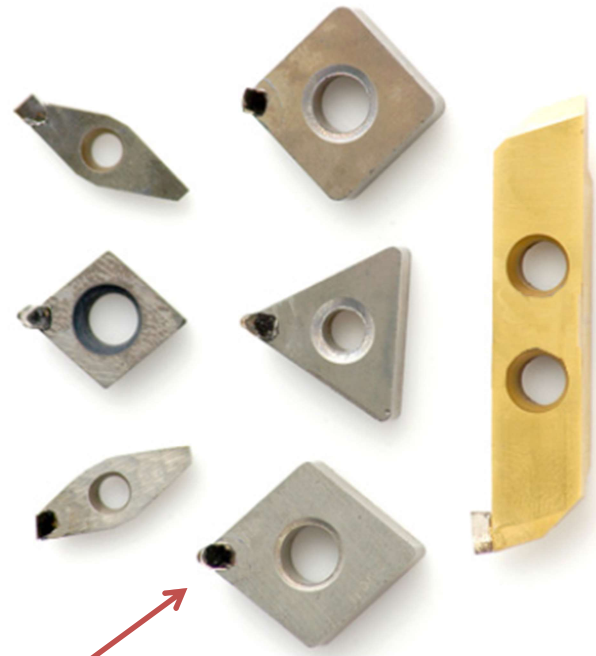
1. Accuracy of process
2. Rigidity of machine
3. Quality of cutting tool

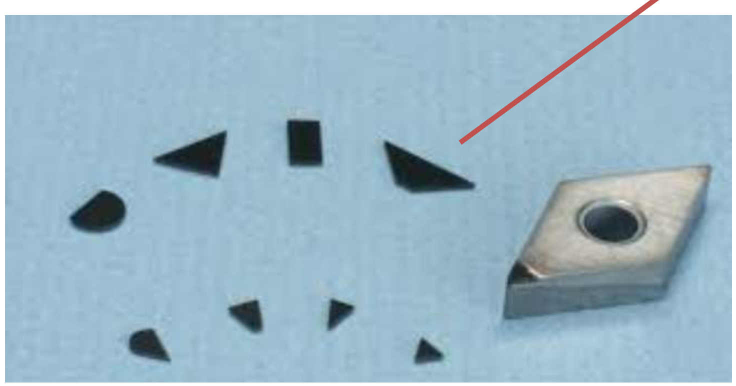
Requirements of DTM tools

- ❖ Tools should retain sharpness over a long period of time.
- ❖ Tool should also have good

1. Strength
2. Hardness & hot hardness
3. Heat conduction
4. Wear resistance
5. Toughness
6. Elastic & shear modulus to withstand deformation

DTM Tools





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DTM Tool Geometry

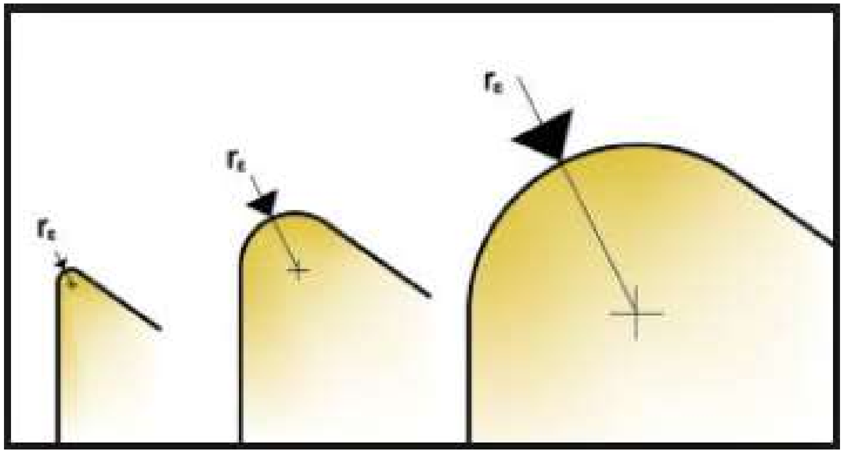
❖ Key features are,

1. Tool nose radius
2. Rake angle
3. Clearance angle
4. Sharpness of cutting edge
5. Accuracy or waviness of the cutting edge.

Tool Nose Radius

Ranges between 0.2mm – 0.3mm

- As tool nose radius decreases surface finish increases but tool life reduces.



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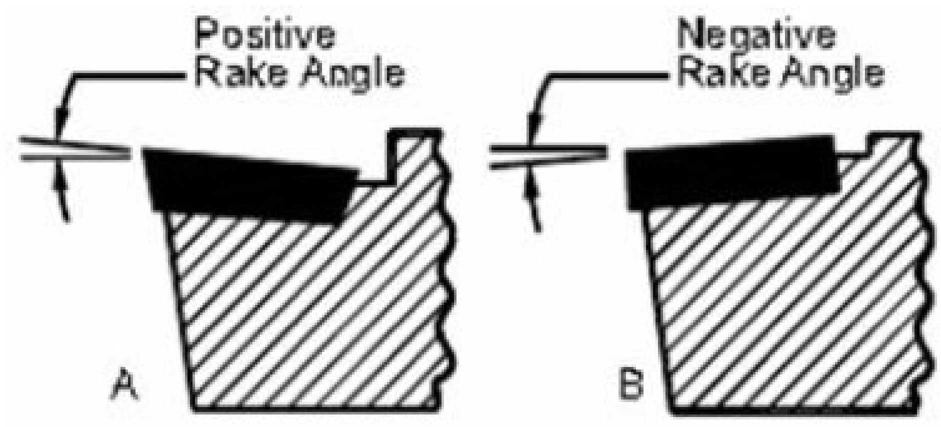
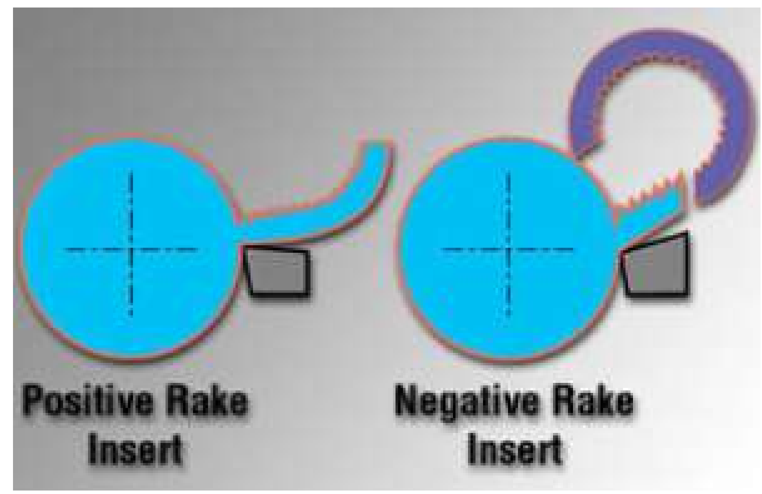
Rake Angle (0 to –45^0)

- Negative rake angle reduces metal removal rate but improves surface finish.





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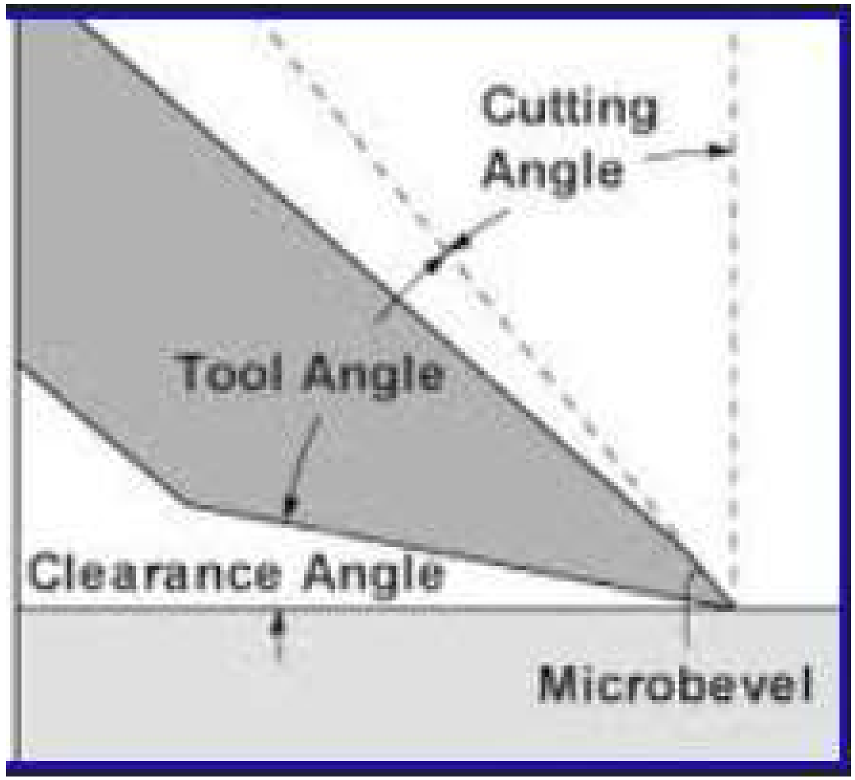
Clearance Angle ($10^0 - 15^0$)



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Sharpness of tool

- As sharpness of cutting edge increases quality & finish of machining also increases.
- Sharp tools reduces residual stresses & sub surface damages.
- Commercially available tools are sharpened to 100-200 nm nose radius.

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Accuracy or waviness of the cutting edge

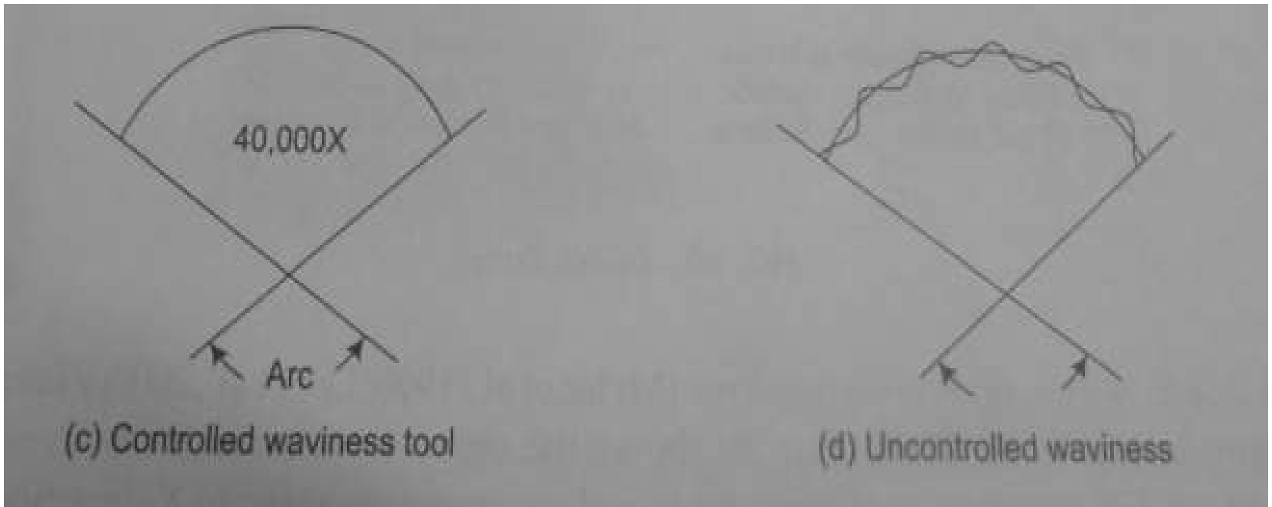

FIG. 19 Diamond Tool Waviness Errors

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Tool Setting

- Tool should be precisely positioned with respect to both lateral directions (X & Z axis).
- Centre height of the tool should be considered before off setting the tool.

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Applications of DTM

1. Non spherical lenses & mirrors
2. Aluminium substrate for compact discs
3. Drums of photo copying machines
4. Moulds for lens manufacturing
5. Metal mirrors for laser applications
6. Missile cones... etc…..

Applications of DTM

1. Al telescope mirror
2. Cu helix
3. Al off-axis parabolic
4. ZnSe diffractive asphere lens
5. Cu phase retarder
6. Cu Total Reflector
7. 45 pressure controlled variable radius mirror (VRM)
8. Cu waxicon
9. Cu output scrapper mirror
10. Cu spiral mirror
11. ZnSe vortex lens
12. Al parabolic mirror
13. Cu rooftop beamsplitter
14. Al off-axis parabolic
15. Al reflector
16. Cu toroid rear reflector
17. ZnS MS asphere meniscus lens
18. ZnS MS negative meniscus asphere lens
19. Parabolic replica mold
20. Ge lens
21. Cu button mirrors
22. ZnSe transmissive beam integrator
23. Cu reflective beam integrator
24. Cu tophat

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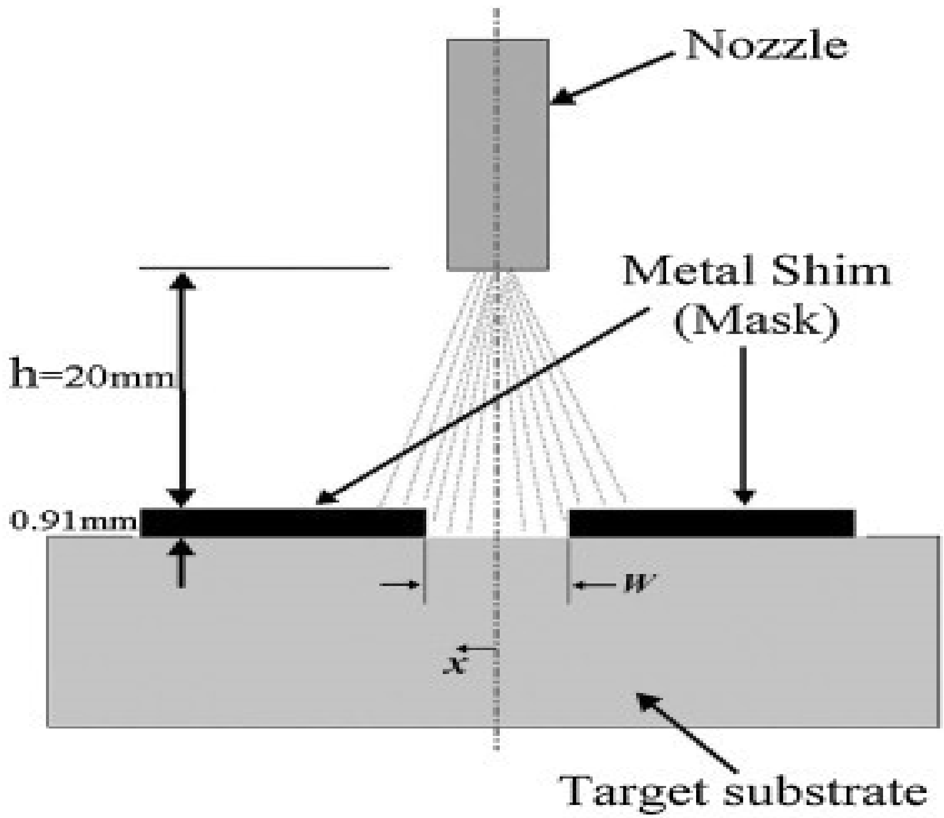
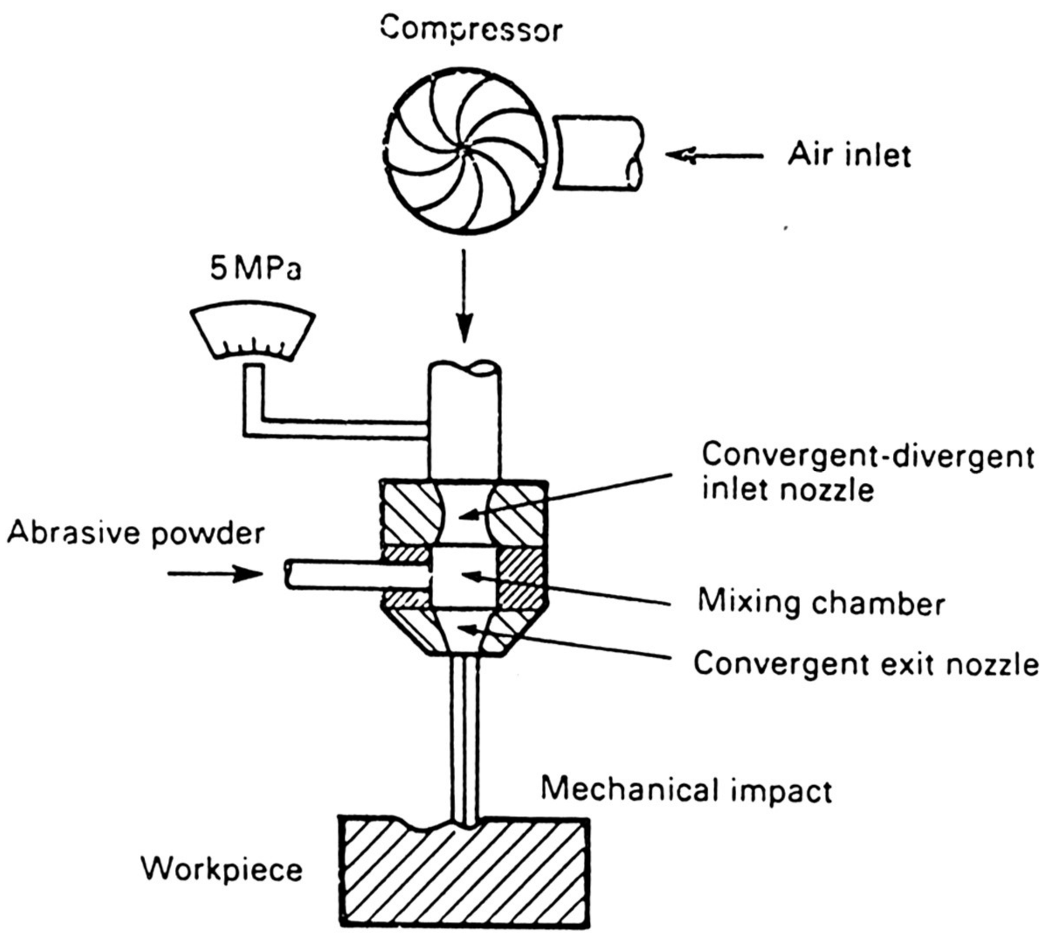
Abrasive Jet Micromachining (AJMM)



Abrasive Jet Micromachining (Dry type)



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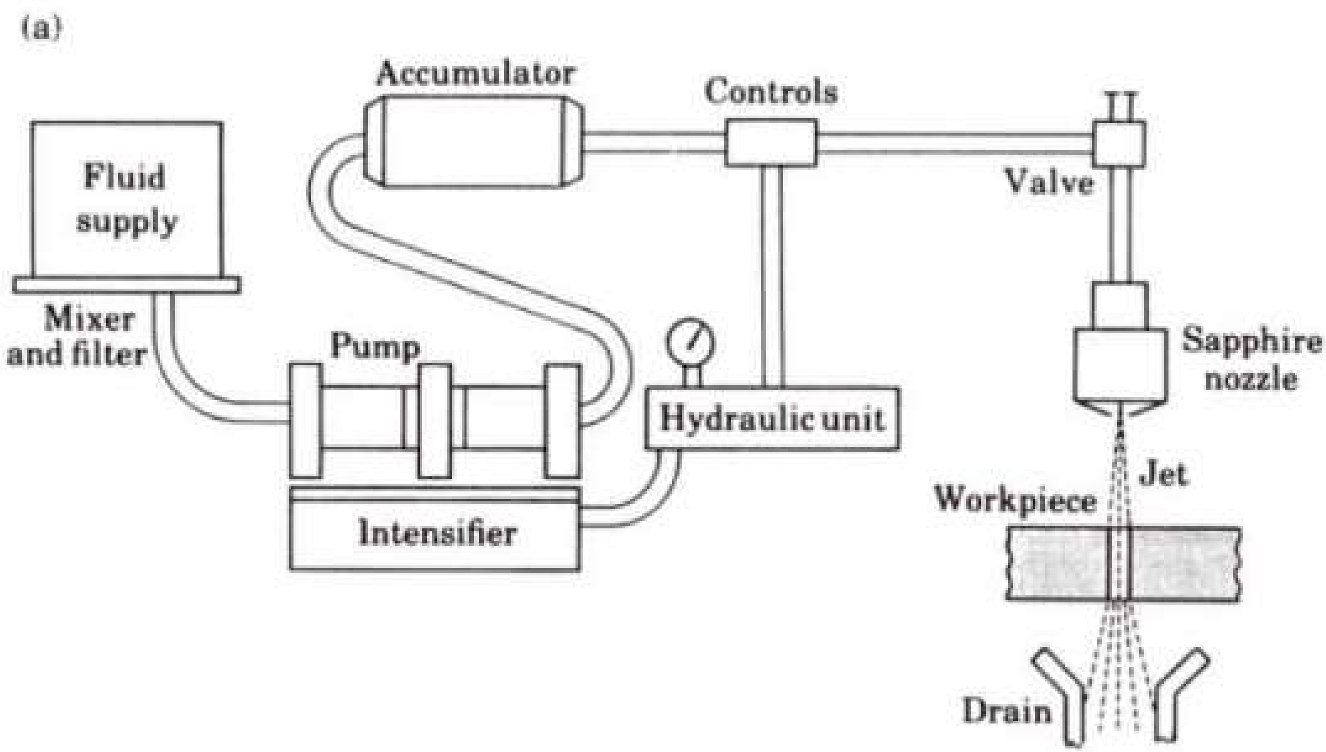
Abrasive Jet Micromachining (Wet type)



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Abrasive Jet Micromachining (AJMM)

- Removal of material is by the application of a high-speed stream of abrasive particles carried in a high pressure – high velocity gas medium from nozzle.
- It differs from conventional sand blasting as much finer (60 μm) abrasive is used and cutting parameters are carefully controlled.
- Typical values:

Pressure of air jet	: 2 - 8 MPa
Orifice diameter of nozzle	: 0.15 – 2 mm
Stand off distance	: 2 – 15 mm
Mass flow rate	: 4 – 15 g/min

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AJMM

- ❖ Influencing elements/factors:
- ➢ 1.Nozzle – geometry, stand off distance.
- ➢ 2.Abrasives – Composition, Strength, size, shape and flow rate.
- ➢ 3.Carrier gas – Composition, pressure, velocity

Elements of AJMM

- **1.Nozzle**
- Abrasive particles are directed into the work surface at high velocity.
- Material of nozzle should be very hard and should have high resistance to wear.
- Eg. Tungsten carbide, sapphire.
- Nozzle can have either circular or rectangular shape.
- **2.Abrasives** –
- Aluminium oxide (Al_2O_3) is used for majority of applications.
- Silicon carbide (SiC), Sodium bicarbonate, dolomite etc are also used.
- Abrasives cannot be re-used.
- **3.Carrier Gas**
- Eg. Air, Nitrogen, CO_2 etc

Advantages & Disadvantages of AJMM

❖ <u>Advantages:</u>

- Ability to cut complex hole shapes in materials of any hardness and brittleness.
- Ability to cut fragile and heat sensitive materials without damage.
- Low capital cost.

❖ <u>Disadvantages:</u>

- MRR is slow and hence its applications are limited.
- Accuracy is less as stray cutting can occur.
- Embedding of the abrasive in the work piece may occur while machining soft materials.

Applications of AJMM

- Machining of brittle and heat sensitive materials like glass, quarts, sapphire etc.
- Drilling holes, cutting slots, cleaning hard surface, deburring, scribing, grooving, polishing etc.

Masking Technology in AJMM

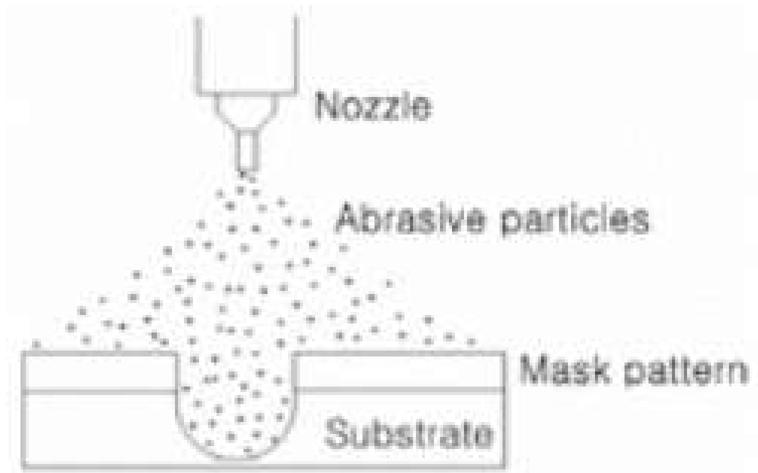

Fig. 1. The principle of micro-AJM with mask pattern.

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Existing Vs New mask fabrication technology

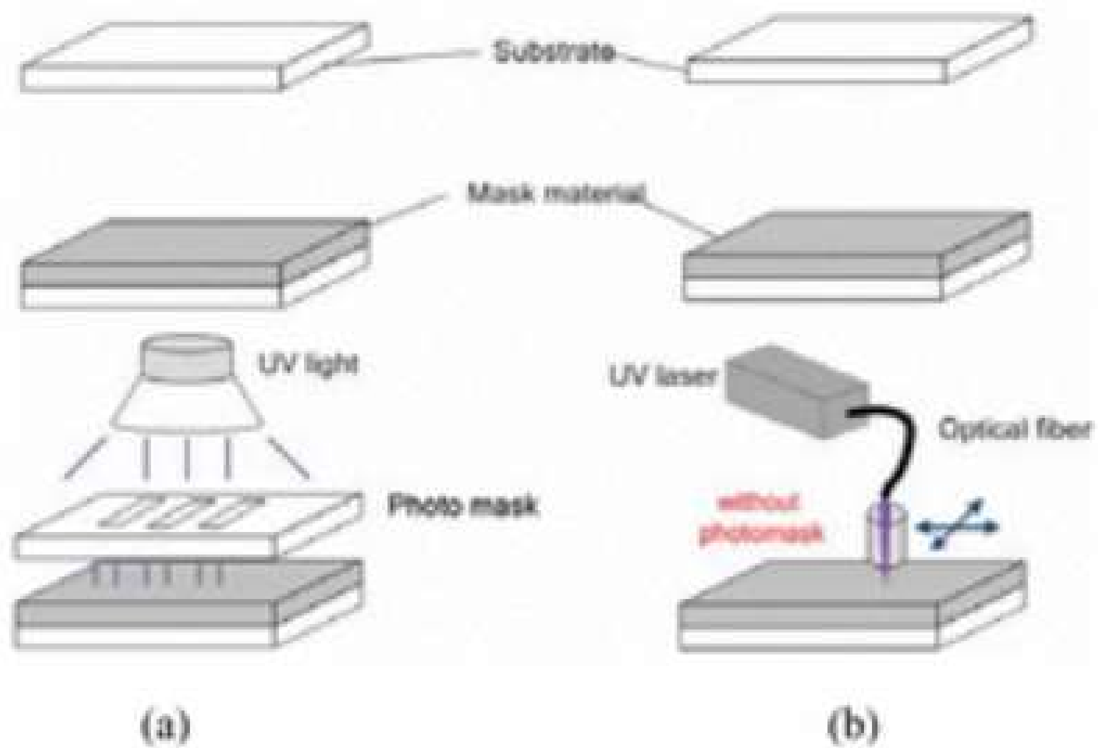

Fig. 2. Comparison of exposure process: (a) Existing mask fabrication technology and (b) New mask fabrication technology.

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Types of Masks

1. Metal mask,
2. Elastomer mask,
3. Photo - resist mask.

Metal Mask

- Ductile materials are used due to their low erosion rate.
- Patterns are created by micro drilling/ micro milling/ laser machining
- Masks are attached using clamps/ adhesives.
- E.g. - Stainless steel, Copper.

Elastomer Mask

- Elastomer is a rubber like material
- Elastomers shows large values of tensile elongation, and due to this property they show elastic deformation during impact.
- Fatigue strength of elastomers are high, so they exhibit good erosion resistance.
- E.g. - Polyurethane (PU)

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Photo-resist Mask

- To with stand highly intensified UV rays.
- E.g. – Epoxy granite

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Erosion Mechanisms

- Erosion mechanism involves plastic deformation & brittle fracture.
- When impact energy exceeds the bond strength, brittle materials erode by crack propagation.
- If impact angle = 90^0 , erosion takes place due to crack propagation & fracture mechanism in brittle materials.
- If impact angle < 90^0 , plastic deformation of ductile materials takes place.

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Mass loss of the Erodent (Work piece)

❖ Mass lose = $K \frac{\rho}{H} \frac{1}{2} mv^2$

- Where K = Constant,

  ρ = Density of eroding material

  H = Hardness of eroding material

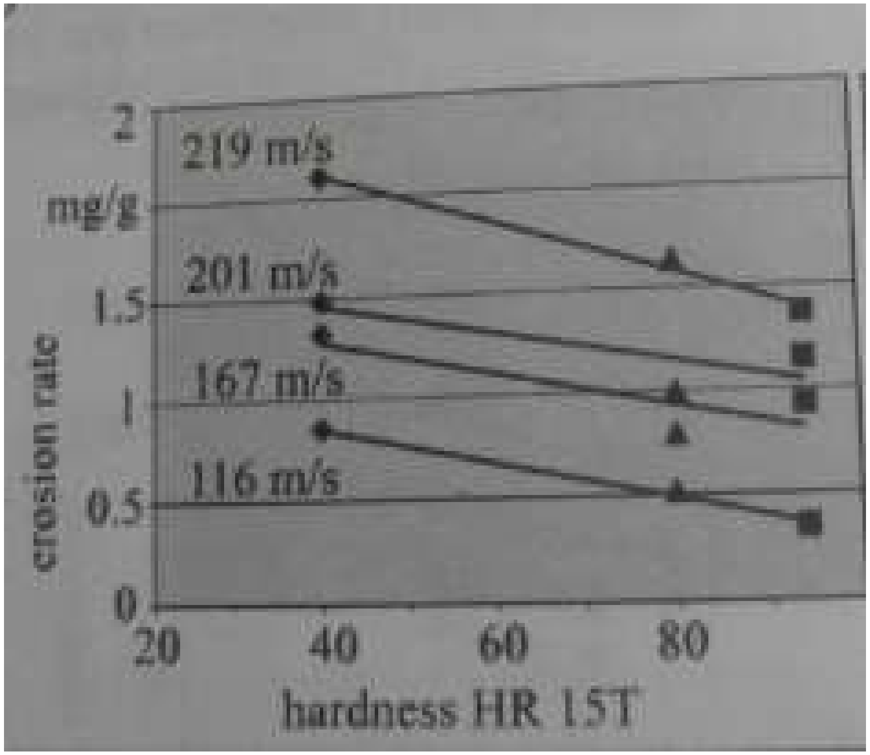
  m = Mass of particles

  v = Velocity of particles

Surface Properties & AJMM

❖ Hardness

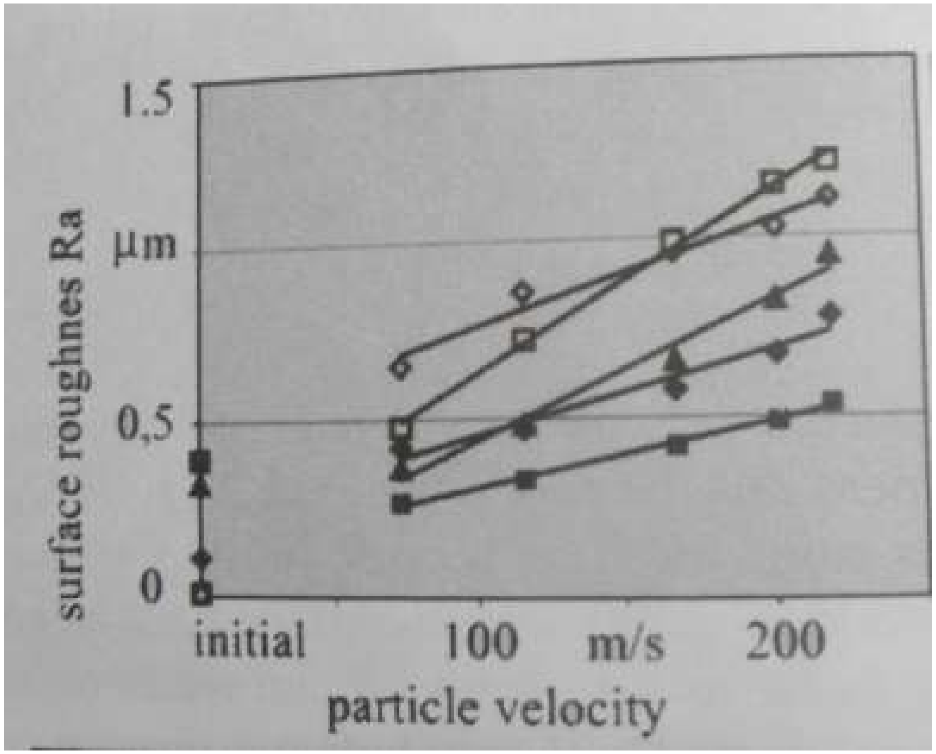
- As hardness of work piece increases, erosion rate decreases.



Surface Properties & AJMM

❖ <u>Roughness:</u>

As particle velocity increases, surface roughness increases.



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Constant Powder Feeding

1. Pressurized Powder Feed System
2. Fluidized Bed Powder Spray System

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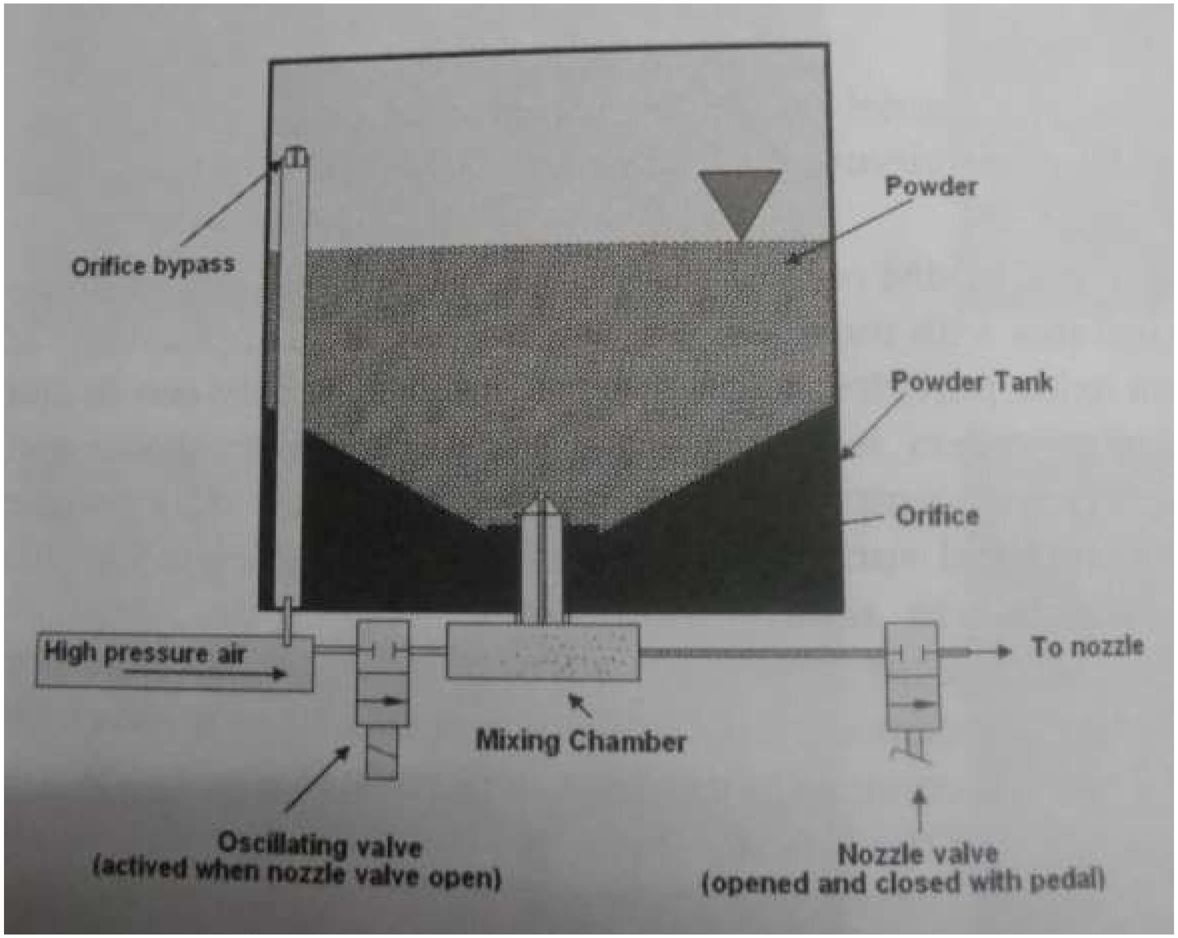
Pressurized Powder Feed System



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Fluidized Bed Powder Spray System

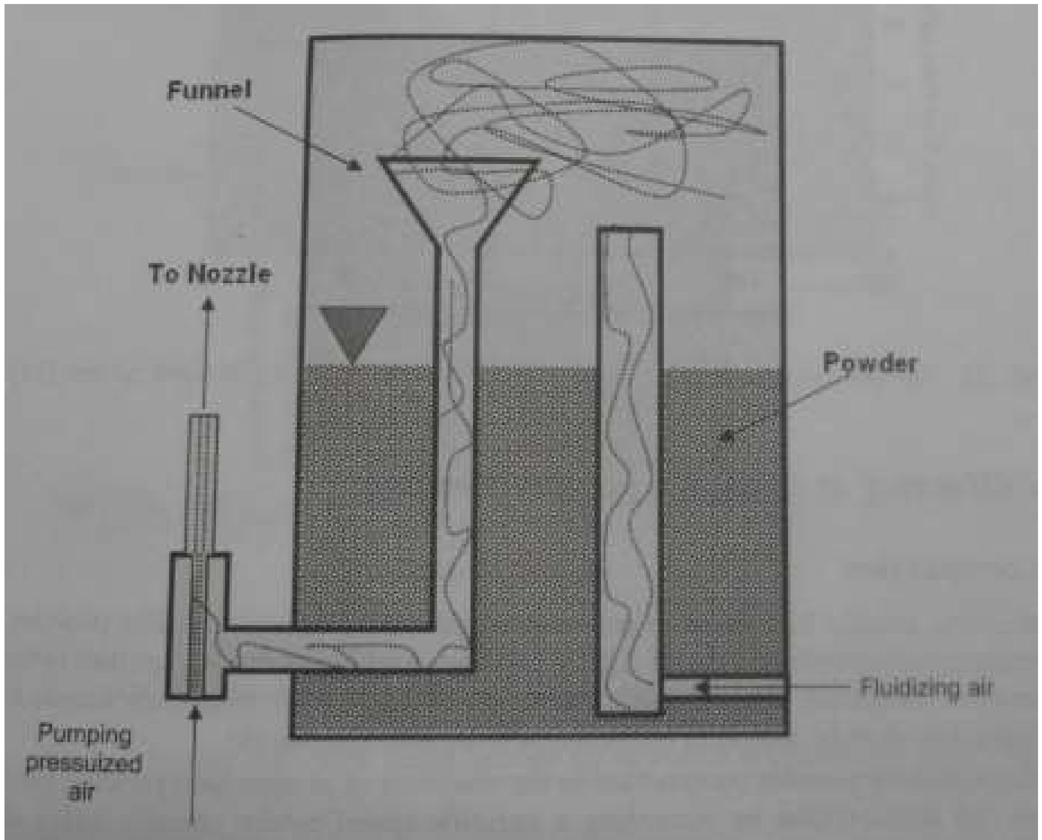

FIG. 13 Schematic of fluidized bed powder spray system

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Factors affecting constant powder feeding

1. Powder compaction
2. Reservoir powder level
3. Powder stratification
4. Powder humidity

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Factors affecting constant powder feeding

1. Powder Compaction

- **Advantages of proper compaction:**

1. Ensure sufficient flow of abrasives
2. Increases velocity of particles

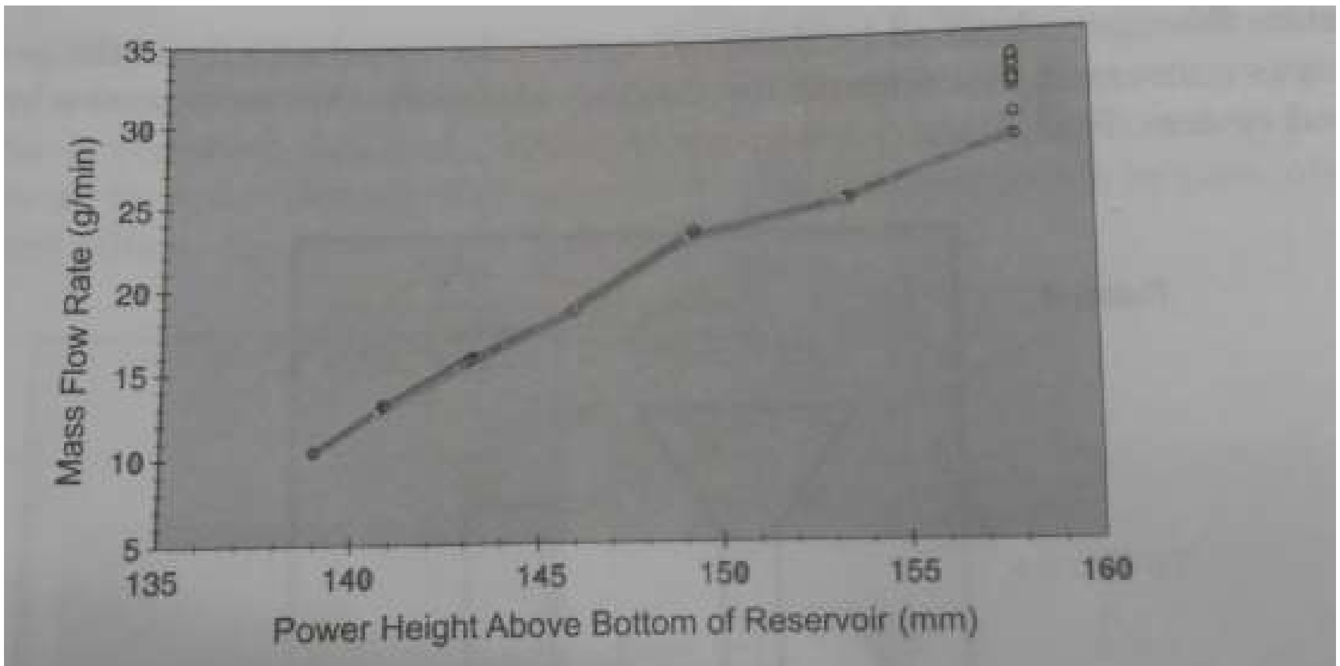
- **Disadvantages of improper compaction:**

1. Will affect the free flow of abrasives
2. Formation of cavities near orifice.

Factors affecting constant powder feeding

2. Reservoir powder level

- As reservoir powder level increases, mass flow of abrasive particles also increases.



5 Powder mass flow rate as a function of powder level in fluidized system

Factors affecting constant powder feeding
3. Powder Stratification

- During blasting, stratification of abrasive particle takes place, i.e. smaller abrasive particles are ejected first, leaving the larger ones to remain in the reservoir.
- This will increase the tendency of blocking the nozzle and reduce efficiency of machining.
- Usage of powder bed mixer blade can reduce powder stratification.

Powder bed mixer blade

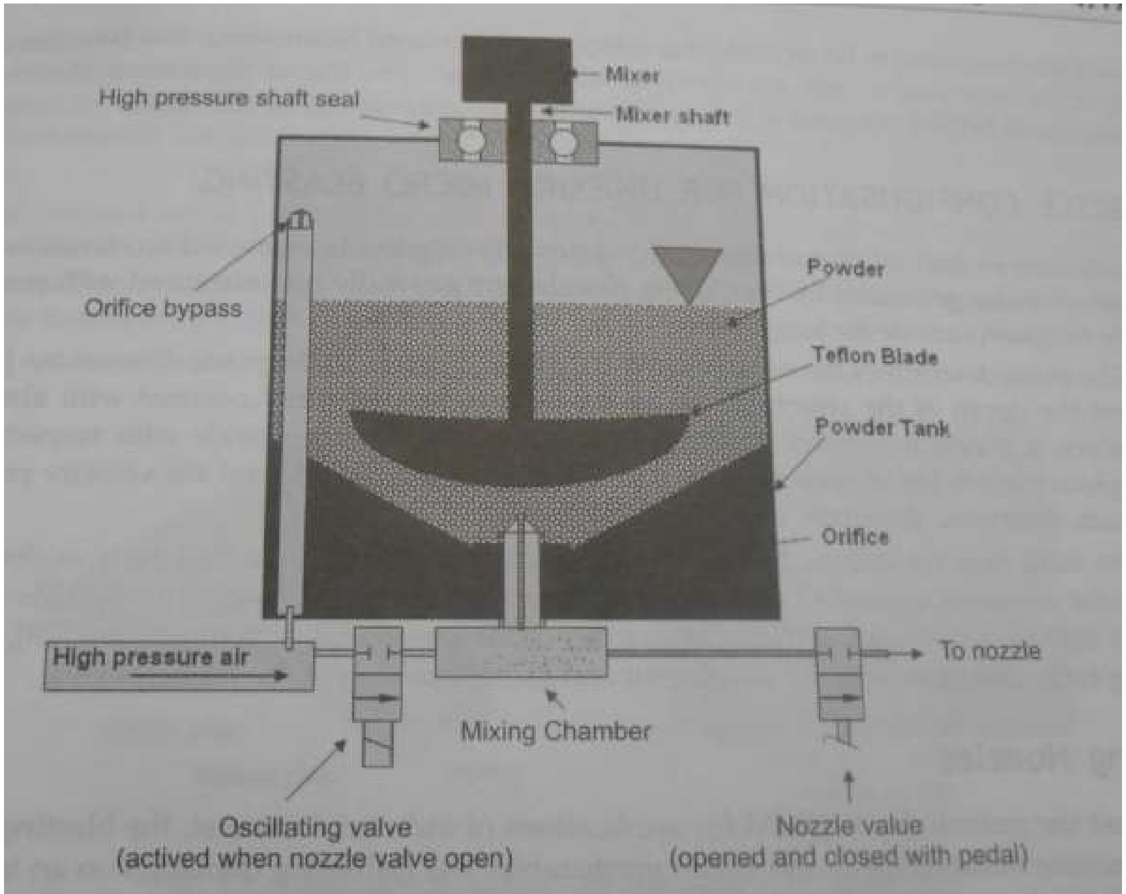


FIG. 16 Powder bed mixer blade located above orifice in pressurized reservoir

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Factors affecting constant powder feeding

4. Powder Humidity

- Humidity decreases toughness of abrasives.
- Humidity decreases powder flowability and efficiency of machining.
- Usage of powder bed mixer blade can reduce the effect of humidity on abrasive powders.

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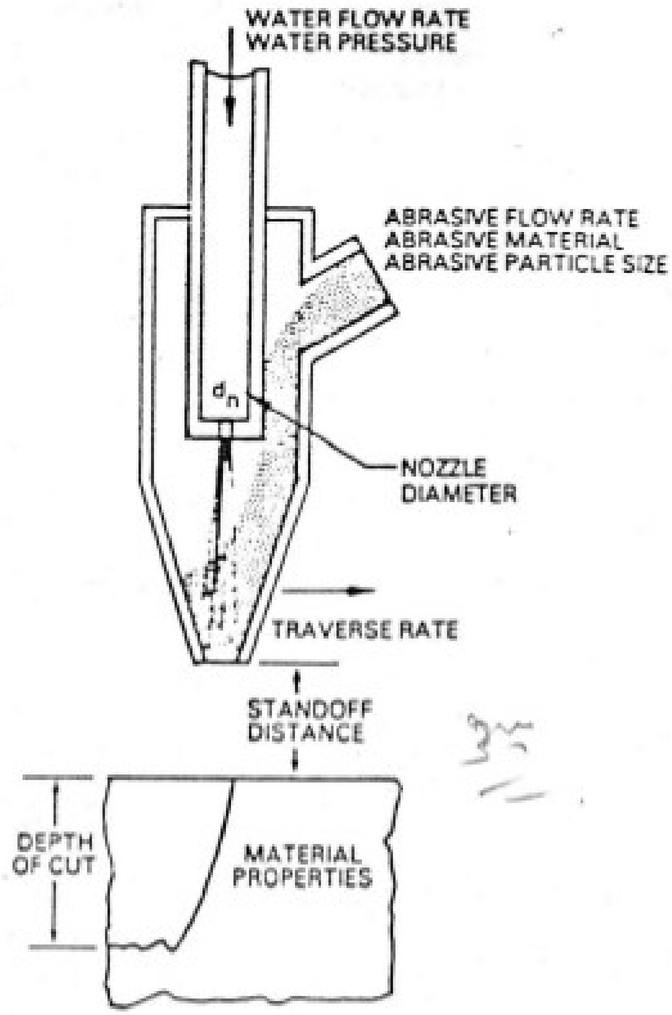
Process Parameters



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AJMM – Process Parameters and their effects

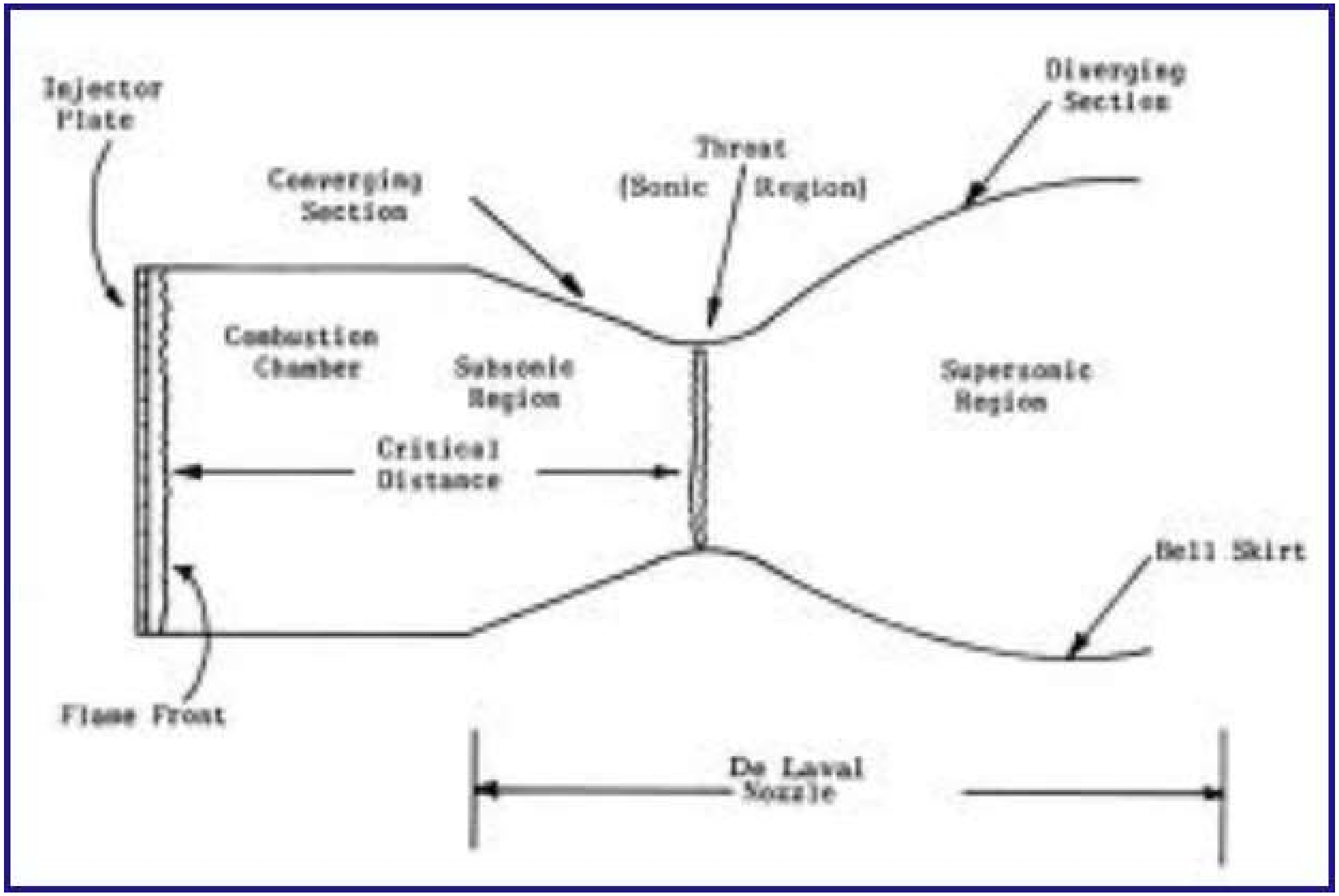
1. **Air flow rate** – As flow increases, MRR increases.
2. **Air pressure** – As pressure increases, MRR increases
3. **Abrasive flow rate** – As flow rate increases, MRR first increase then decreases
4. **Abrasive material** – As hardness increases, MRR also increases.
5. **Abrasive particle size** – As size increases, MRR increases but surface finish decreases.
6. **Nozzle diameter** – Determines the particle velocity.
7. **Traverse speed** – As speed increases, depth of cut reduces, surface finish increases.
8. **Stand off distance** – As distance increases, MRR reduces.
9. **Material property** – As hardness of work piece increases, MRR reduces.
10. **Depth of cut** – As depth of cut increases, surface finish reduces.

Nozzles

- Requirements

1. Pressure-less constant feeding system
2. Supersonic air flow velocity in the nozzle
3. Homogenous dispersion of abrasive particles over the width of the nozzle
4. Long life time

Laval Nozzle



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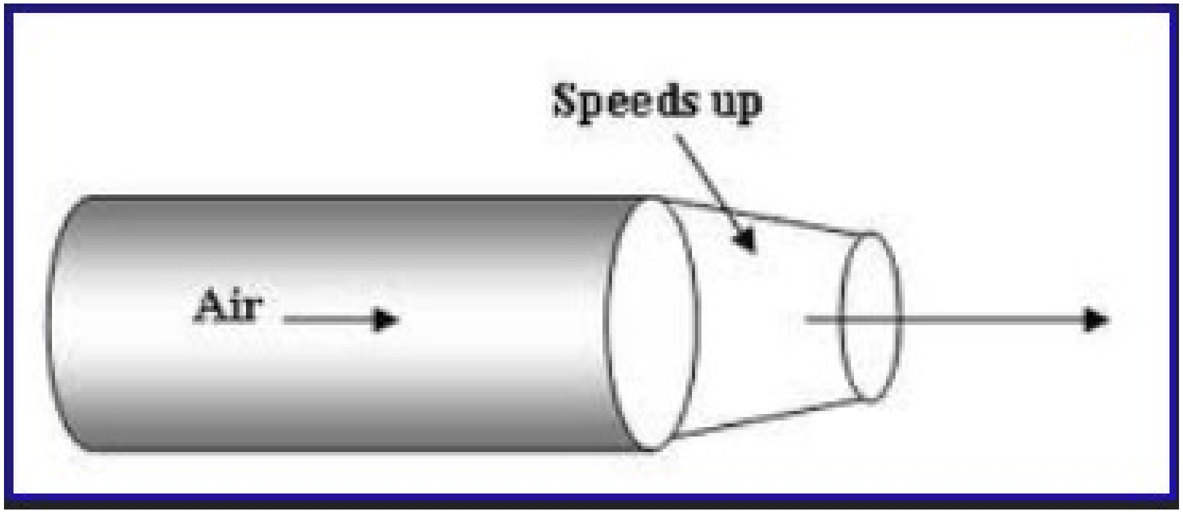
Cylindrical Nozzle



MODULE 2

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Magneto Rheological (MR) Fluid

- **Magneto rheological fluid** (MR fluid) is a type of smart fluid in which abrasive particles are carried in a carrier fluid (usually mineral oil/organic or aqueous liquids).
- When subjected to a magnetic field, the abrasive particles become active and the fluid greatly increases its apparent viscosity, to the point of becoming a viscoelastic solid.

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Magneto Rheological (MR) Fluid

- Apparent Viscosity of MR fluid increases by 10^5-10^6 times within a few milliseconds, when magnetic field is applied. The process reverses as magnetic field is turned OFF.
- Abrasive particle size ranges from 0.5 – 100μm
- E.g. of ferrous abrasives – Iron, ferrites & other ferromagnetic particles.
- E.g. of non ferrous abrasives – (Diamond, Silica, Barium titanate) + Carbonyl Iron Particles (CIPs)
- Excitation is done by Electromagnets / Permanent magnets.

Carbonyl Iron Particles (CIPs)

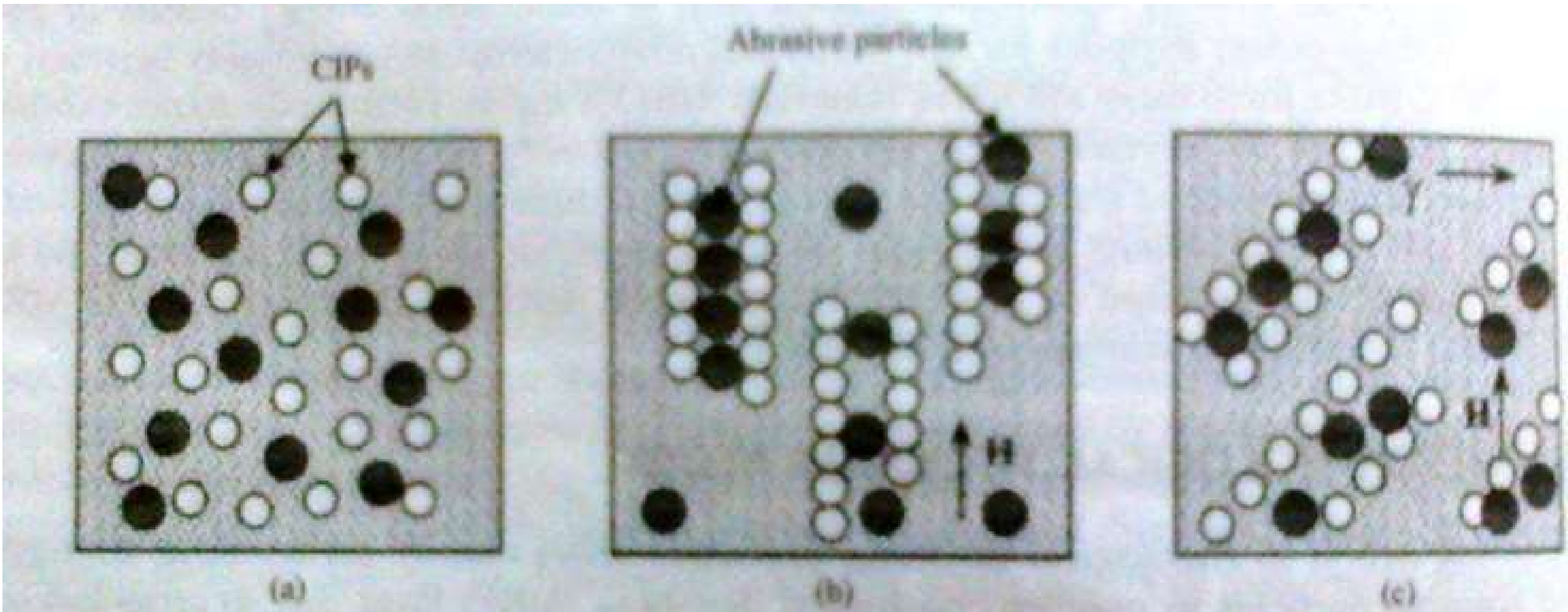

FIG. 2 A schematic diagram to illustrate magnetorheological effect in polishing fluid. (a) No magnetic field, (b) At magnetic field strength H, (c) At magnetic field H & applied shear strain

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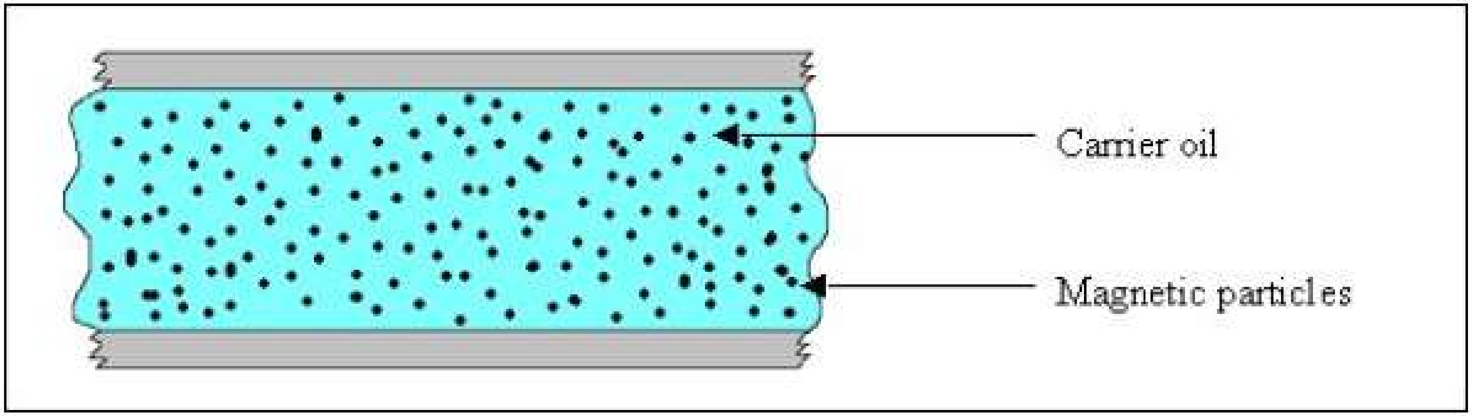
MR Polishing Fluid Nomenclature

MRPF 20 CS 20 SiC 800

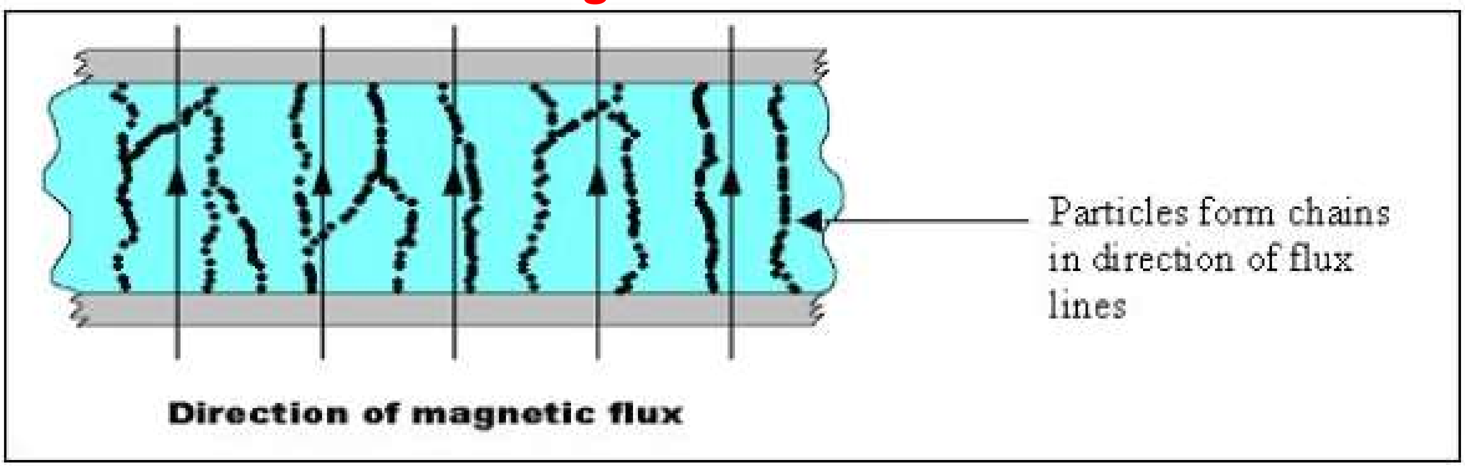
- **Abrasive mesh size**
- **Abrasive type**
- **% Vol. of abrasives**
- **Carbonyl Iron grade**
- **% Vol. of CIPs**
- **Magneto Rheological Polishing Fluid**

Rheological Properties of MR Fluid

Magnetic Field "OFF"



Magnetic Field "ON"



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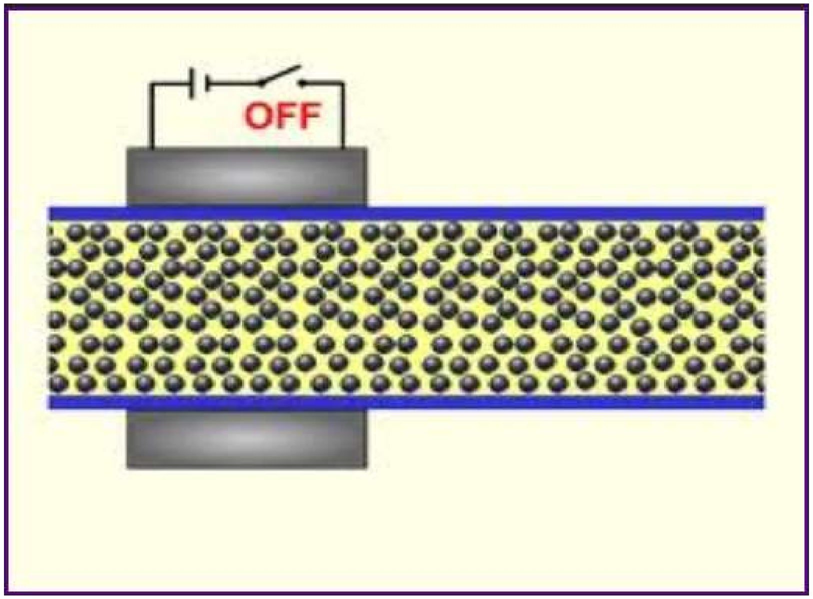
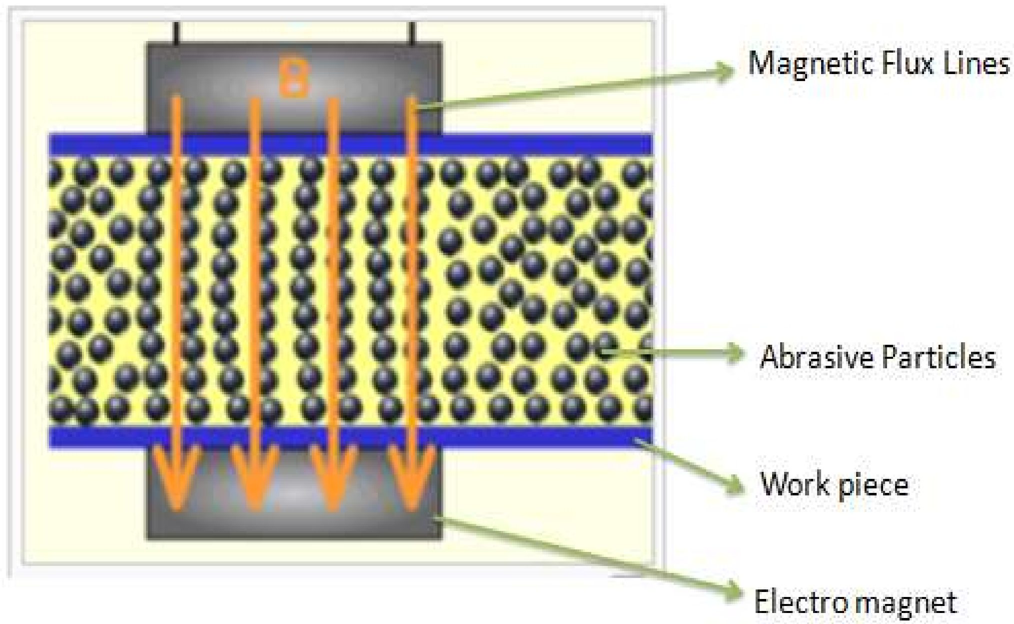
MR Abrasive Flow Finishing Process (MRAFF)





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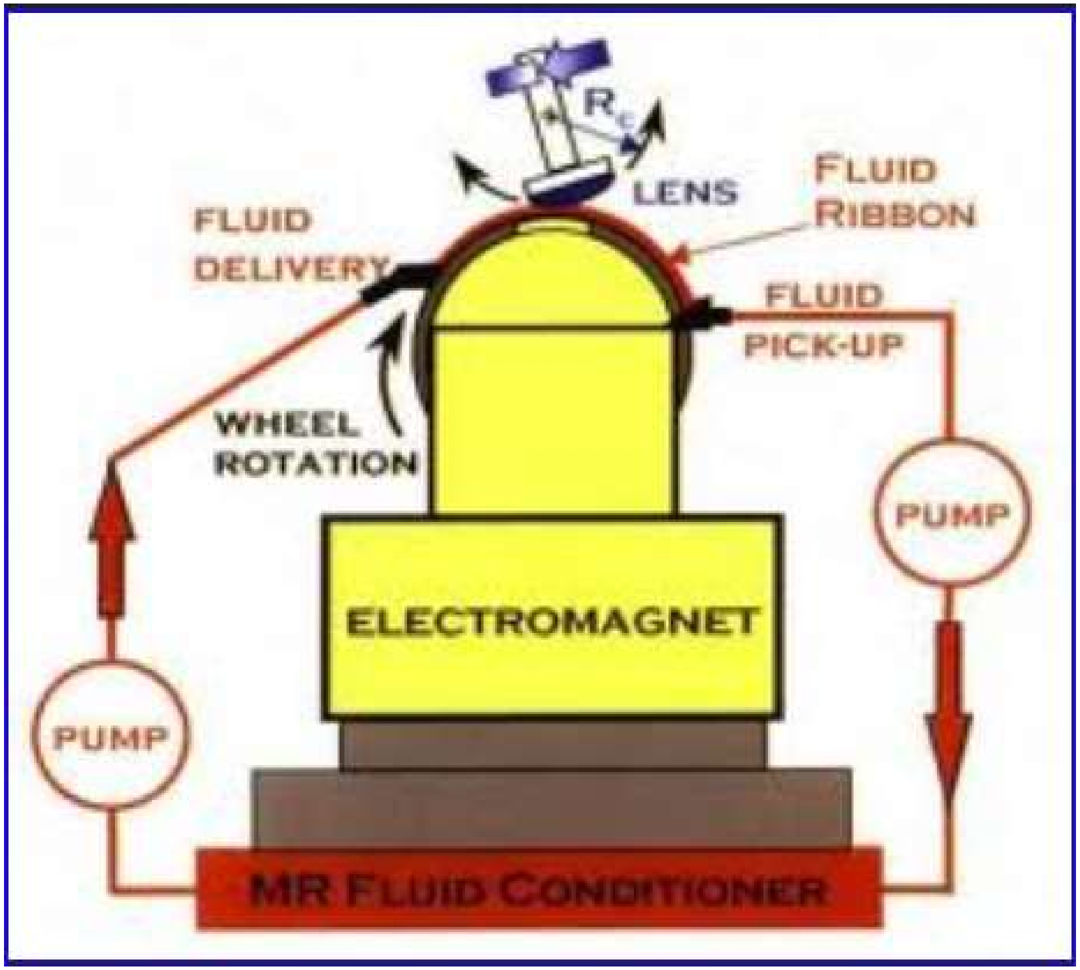
Performance Analysis of MRAFF Process

- Specimen: Flat stainless steel plate (35x5x2 mm)
- Initial Ra value of specimen: 280 nm
- Apparatus used: Atomic Force Microscope
- MR Fluids used: 1) MRPF 20 CS 20 SiC 800
  2) Diamond abrasives.
- Fluid pressure: 3.75 M Pa

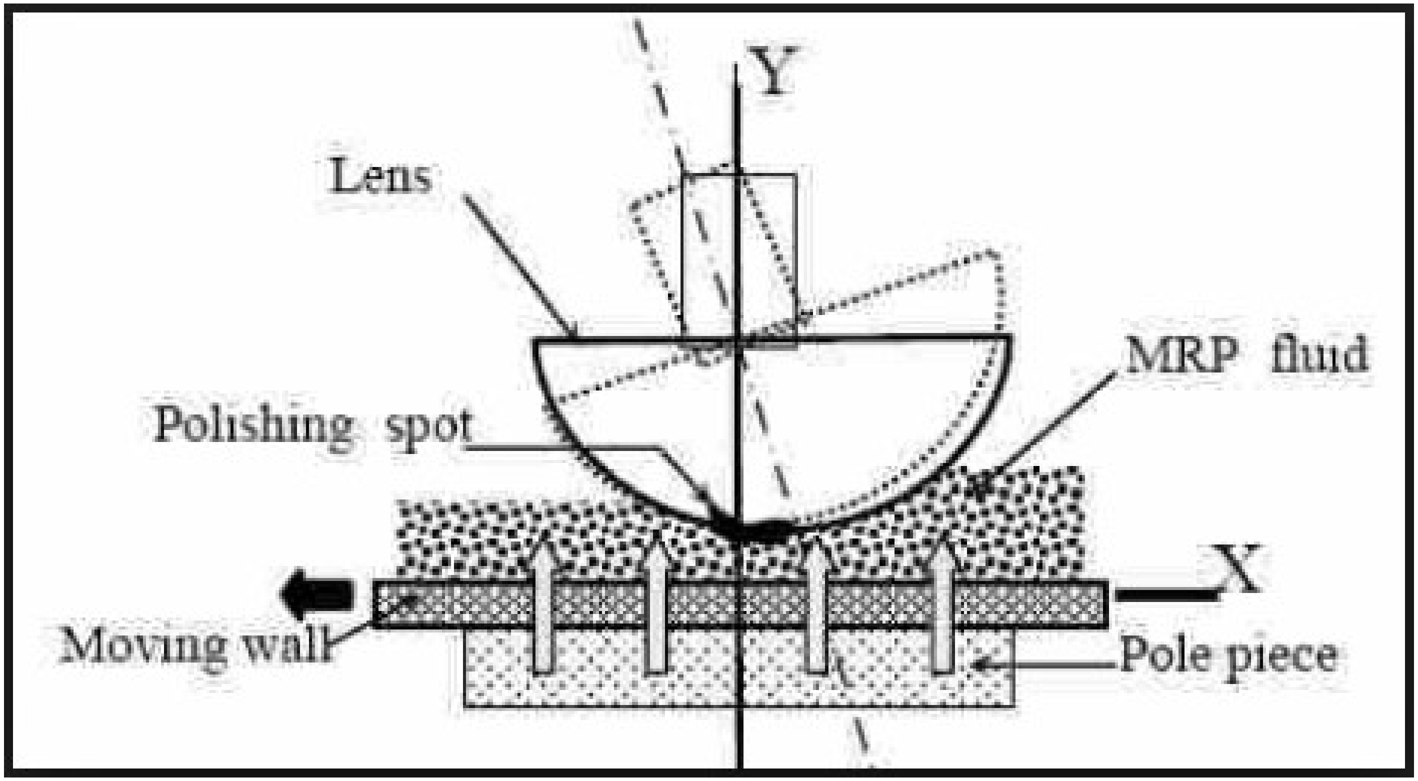
Performance Analysis - Result

- Initial Ra value of specimen = 280 nm
- Ra value after 2000 cycles with SiC abrasives = 100 nm
- Ra value after 3500 cycles with diamond abrasives = 100 nm

MR Finishing Process – Machining of Contact Lens



MR Finishing Process – Machining of Contact Lens



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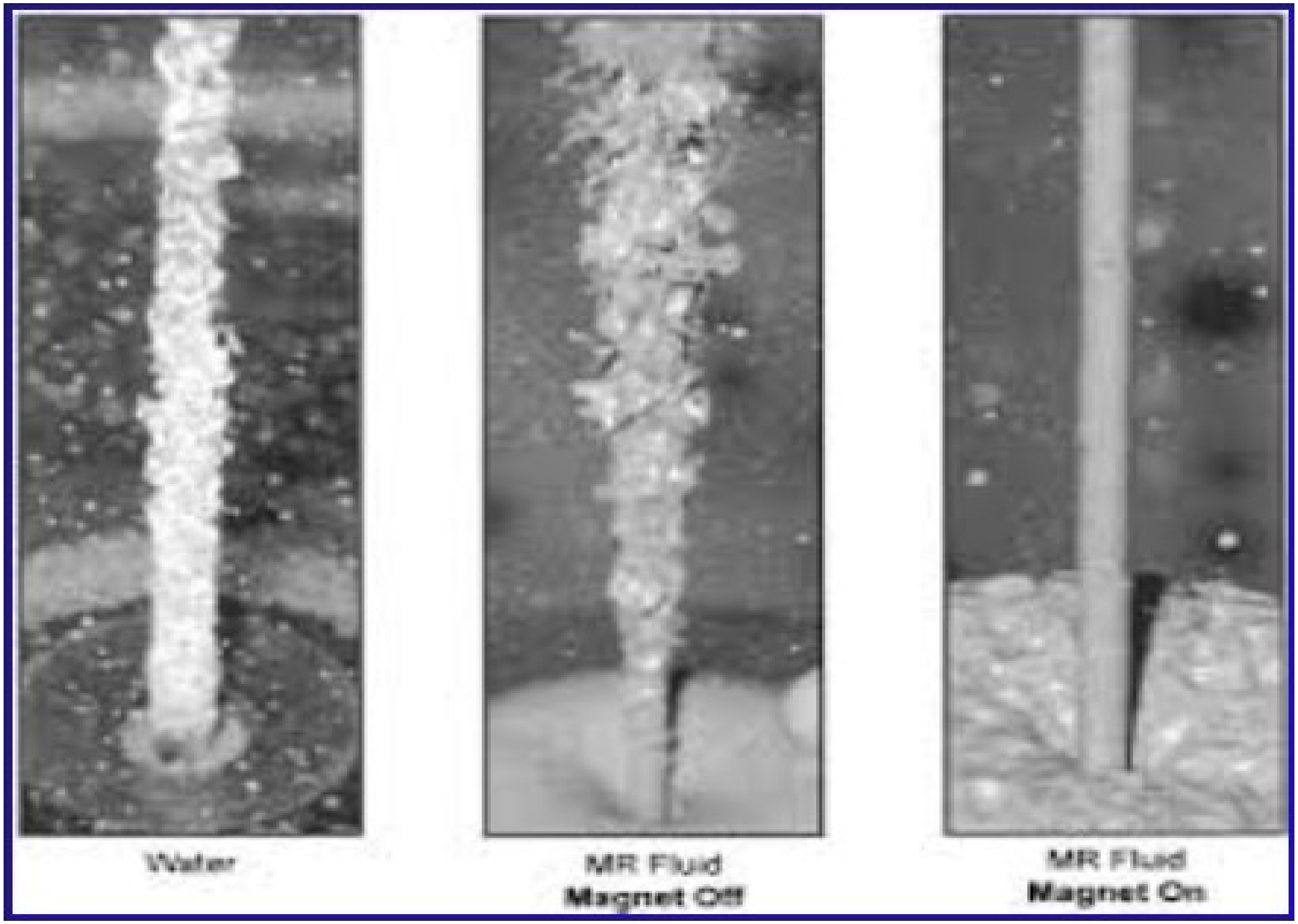
Advantages of MR Finishing over Conventional Grinding Process

1. Can vary the machining rate by varying magnetic field, abrasive flow rate & abrasive type.
2. Carries heat & debris away from the polishing zone.
3. Does not load the work piece like a grinding wheel.
4. It does not lose its shape during the process as it is self deformable.

MR Jet Finishing Process



Working Principle of MR Jet Finishing Process

- Material removal is governed by Kinetic Energy of impacting abrasive particles.
- Surface stresses developed due to the flow of abrasive slurry results in material removal required for polishing.
- Jet stabilization is achieved by magnetizing the tip of nozzle.
- MR fluid jet remain coherent for distance more than 200 times the diameter of the nozzle.

MR Jet Finishing Machine

- A computer code (micro processor) generates machine control programs for polishing.
- Inputs to this code are 1) Material removal spot, 2) Initial surface details.
- Outputs of the machine are machine program instructions in the form of 1) Velocity schedule 2) Prediction of final surface figure.
- The micro processor based software uses series of complex algorithms to derive an operating program for CNC machine.
- The code specifies angles, velocity, no. of cycles required and total estimated processing time.
- The CNC jet finishing machine then executes this program instructions to obtain required surface finish.

Jet Finishing Polishing Performance

- Specimen used: Concave glass inserts placed in aluminium shell.
- Specimen is rotated on its axis & swept around its centre of curvature.
- Jet is kept normal to the optical surface.
- Initial peak-valley error: 470 nm
- Final peak-valley error: Less than 50 nm

Process Parameters of MR Finishing

1. Flow rate of abrasives : As flow rate increases, MRR also increases.
2. Magnetic field: As magnetic flux intensity increases, Viscosity of MR fluid increases & MRR also increases.
3. Abrasive Particles:

   1) As abrasive particles becomes finer, surface finish increases.

   2) As grain size & hardness of abrasive particles increases, MRR increases.
4. Viscosity of MR fluid: As viscosity increases, MRR also increases.

Micro/Nano Finishing with Flexible Flow of Abrasives

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Micro/Nano Finishing with Flexible Flow of Abrasives

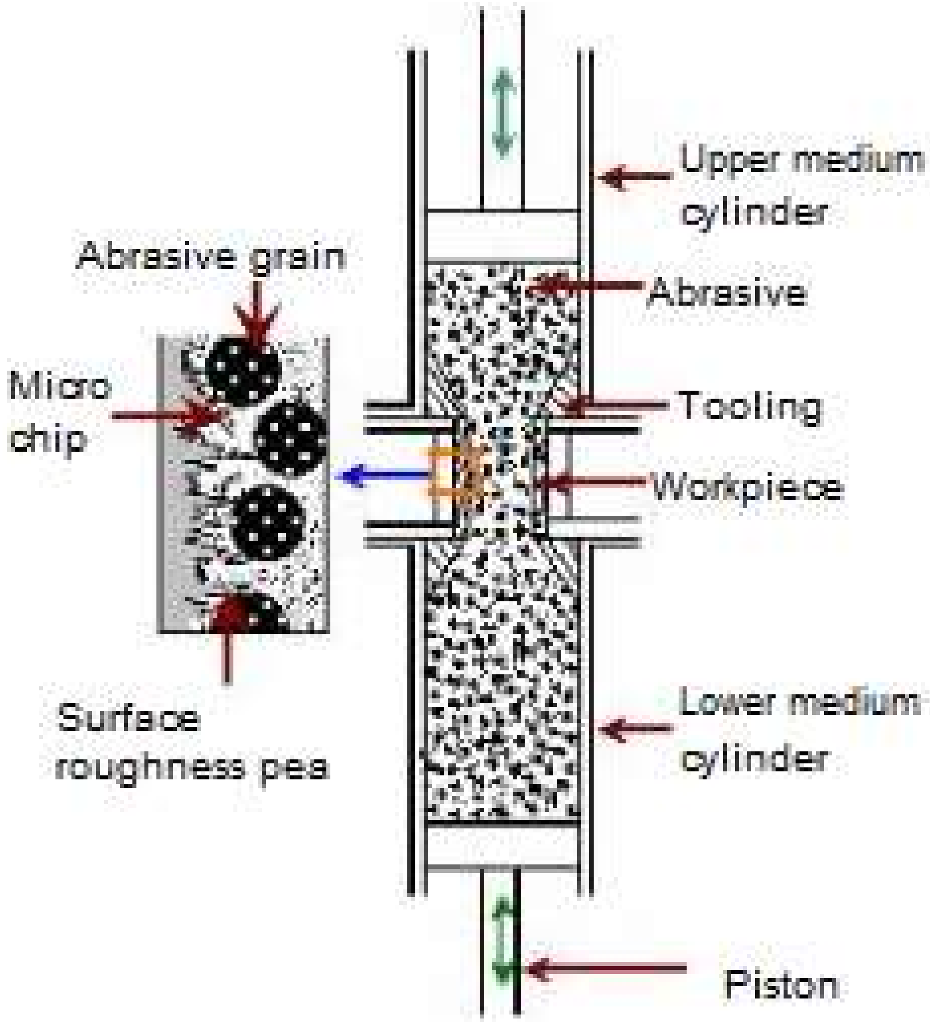

Fig.1: Principle of material removal mechanism in two way AFM process

Process Principle & Description of AFMNF Process

- A semisolid media (consisting of viscoelastic polymer + abrasives) is extruded under pressure through the surface to be machined.
- The media acts as flexible tool/ grinding wheel.
- The deformable ability of media is responsible for its movement through any shape of the passage.
- Work piece is clamped between two vertically opposed media cylinders.
- Fixture/tooling is required to direct & focus the media to the desired locations in the work piece.
- The media is then extruded from the lower to upper cylinder through the work piece.
- One complete up ward & down ward stroke completes a process cycle.

AFMNF - Process Technology / Elements

- Consists of

1. Machine,
2. Media (Abrasive medium),
3. Tooling.

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Process Technology

- Machine : Decides the extent of abrasion,
- Media : Decides the kind of abrasion,
- Tooling : Decides the exact location of abrasion.

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Process Technology

1. Machine

- Consists of positive displacement hydraulic system.
- Force the abrasive media through the work piece at selected pressure & flow rate.
- Pressure ranges from 10 – 200 bars
- Flow rate – ranges upto 225 Liters/Min.

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Controls of AFMNF Machine

- AFMNF Machine has controls on:

1. Hydraulic pressure
2. Clamping & unclamping of fixtures
3. Volume flow rate of media
4. Advancement & retraction of media pistons

Accessories of AFMNF Machine

1. Automatic flow timers
2. Cycle counters
3. Pressure & temperature flow valves
4. Media heat exchangers
5. Media re-feed units

Process Technology

2. Media

- Media consists of base material/carrier + abrasive grains + additives.
- Base material to abrasive grains ratio ranges from 2 - 12
- Additives are added to improve the flowability, lubrication & corrosion resistance.
- E.g. of carrier: Viscoelastic polymer, Rheopetic fluid.
- E.g. of additives: Hydro carbon for improving lubrication.
- E.g. of abrasives: SiC, Boron carbide & Diamond particles…

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Process Technology

3. Fixture/ Tooling

- Main function of the fixture is to hold the work piece in proper position between two cylinders.
- Fixture/tooling directs the media to areas which requires machining.
- Steel, Urethane & Nylon are mainly used for making fixtures.

Selection of Media

- Media consists of base/carrier + abrasive + additives.
- Viscosity of base material, abrasive type & quantity of abrasive particles determines the basic properties of media.
- Media should be sufficiently viscous (should be "rubber like") to hold the abrasive particles against the surface to be machined.
- Less viscous media is used for machining small holes.

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Viscosity of Media

Base 10 – Base 20 – Base 30 – Base 40 – Base 50 – Base 60 – Base 70

→

Low Viscosity **High Viscosity**

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Process Parameters of AFMNF Process

- Media flow rate: As media flow rate increases, MRR increases.
- Extrusion pressure: As extrusion pressure increases, MRR increases.
- Viscosity of media: As viscosity increases, MRR & surface roughness increases.
- Material property of work piece.
- Surface condition of work piece.
- Media characteristics: Abrasive particle size, hardness, flowability…
- Number of strokes.

Material Removal Mechanism

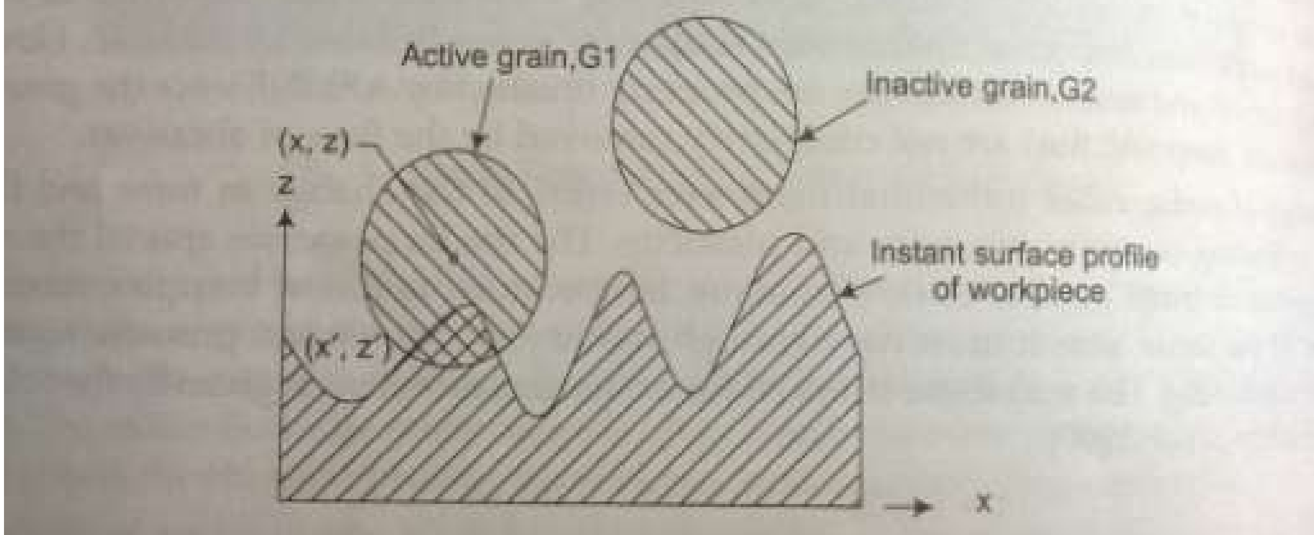

FIG. 6 Schematic of action of abrasive particle during AFMNF (Jain et al. 1999)

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Process Capability

- The inaccessible areas in components, which are impossible to finish with traditional methods, can be finished by AFMNF.
- 90% improvement in original roughness can be attained.
- Media can flow through holes ranging from 20-750 μm

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Applications of AFMNF

- Improving airfoil surfaces of compressor & turbine components.
- Finishing of holes with complex contours,
- Improvement of fatigue strength of blades, shafts…
- Adjustment of air flow resistance of blades, vanes, nozzles…
- For finishing bearing components & dies.
- Reworking the components to remove coke, carbon & aluminide deposits/coatings.

MODULE 3

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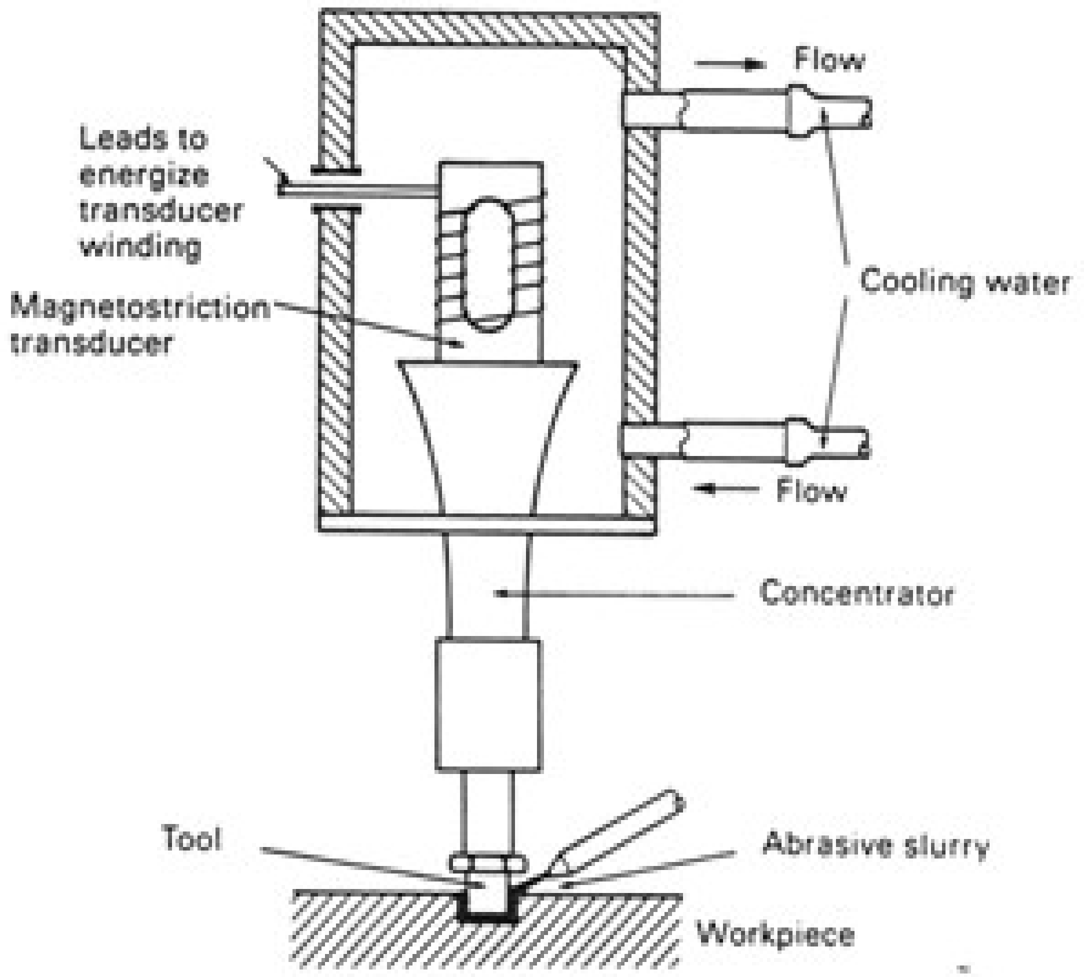
Ultrasonic Machining (USM)



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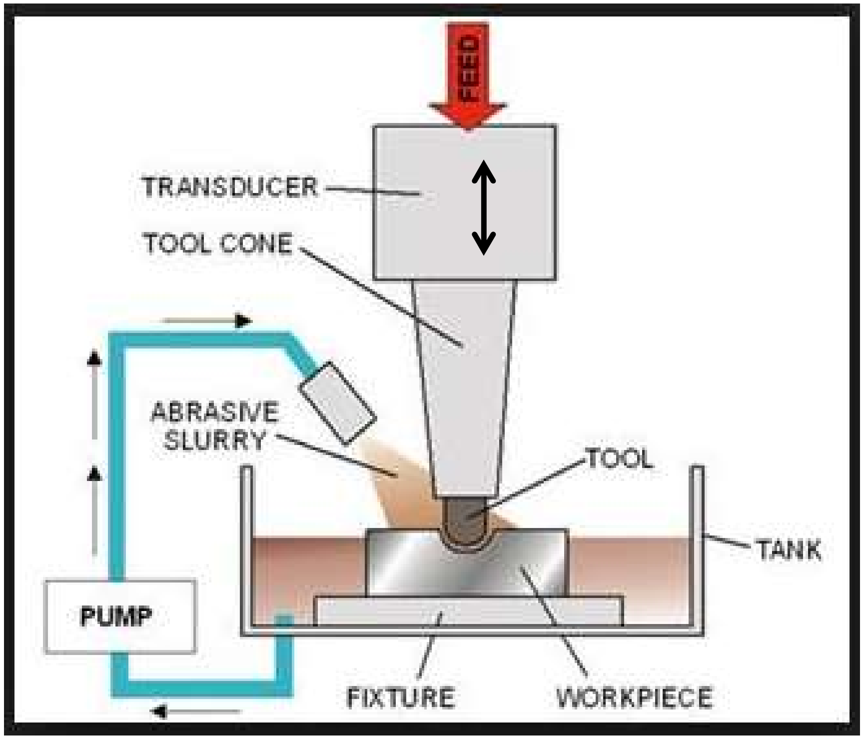
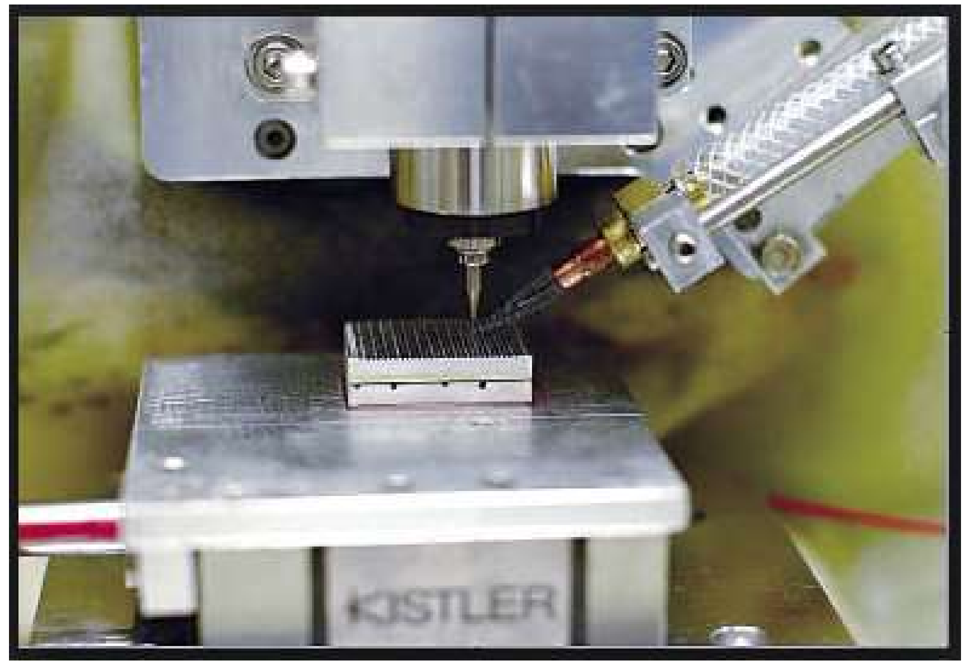
USM





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Ultrasonic Machining (USM)
Vs
Ultrasonic Micromachining (USMM)

USM	USMM
1. Less accurate	More accurate
2. Poor surface finish	Good surface finish
3. Cannot machine holes with dia. <100μm	Can machine holes with dia. = 20 μm
4. No servo motors & sensors used	Uses servomotors & precise motion sensors
5. Tool does not rotate, but vibrates on longitudinal direction.	Additional rotational motion to tool is provided.

Working Principle of USM

- The process starts by applying high voltage to the transducer.
- The transducer will vibrate in linear direction at high frequency (> 20kHz)
- The high frequency mechanical motion is then transferred to the tool via a coupler/tool holder.
- The tool vibrates with a tool extension of only a few hundredths of a millimeter.
- The tool is shaped conversely to the desired shape of cavity.
- The gap between tool & work piece is flooded with abrasive slurry. (Water/oil + abrasive particles)
- The sudden impact of abrasives & abrasion by the contacting particles are the main causes of material removal.

Principle of USM

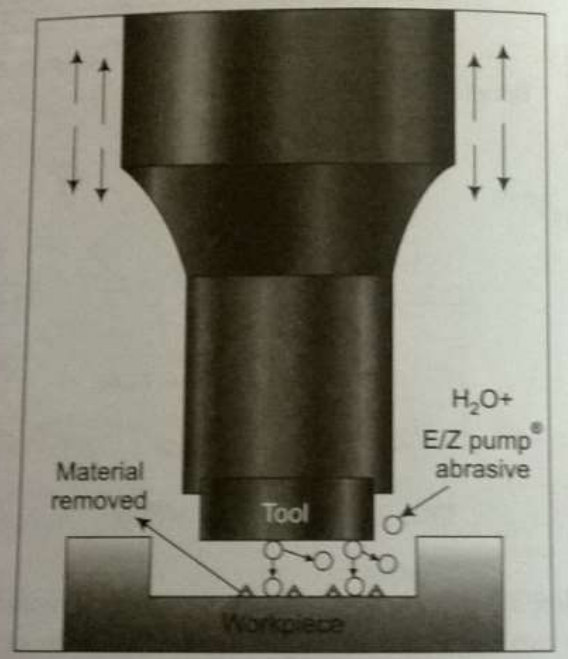
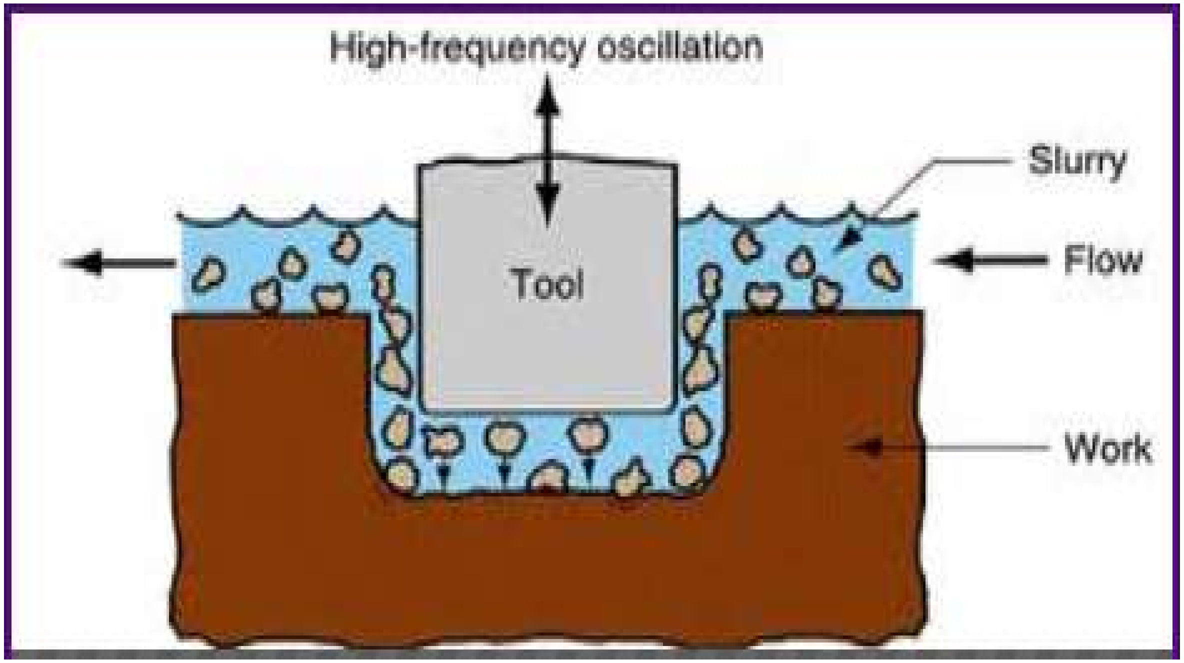


FIG. 3 Principle of USM



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Elements of USMM

1. High Frequency Oscillating Current Generator
2. Acoustic Head
3. Tool spindle mechanism
4. CNC Controller
5. Micro-tool
6. Abrasive slurry
7. Work piece

Elements of USMM

1. High Frequency Oscillating Current Generator

- Primary function of the generator is to convert low frequency electrical power to high frequency
- Consists of a resonance circuit, which when electrically tuned, generates high frequency electrical impulses.
- Output ranges from 5 – 15 kW.
- Frequency ranges from 10-22 kHz

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Elements of USMM

2. Acoustic Head

Consists of Transducer & Horn

- Transducer: Converts high frequency electrical impulses received from generator to high frequency mechanical vibrations.
- Two types: Piezoelectric type & Magnetostrictive type

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Elements of USMM

- Horn is also called acoustic coupler/ mechanical transformer/ concentrator/ shank/ stub/ sonotrode.
- Material used for horn should have

1. High fatigue resistance,
2. Good Brazability,
3. High resistance to wear & tear
4. Good corrosion resistance.

E.g. of horn materials – Monel, Titanium, AISI 304 Stainless Steel & Aluminium Bronze alloy.

Elements of USMM

3. Tool Spindle Mechanism:

- Consists of bearing, mandrel & DC motor.
- By providing rotating motion to the tool, 5μm diameter hole can be machined with high accuracy.

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Elements of USMM

4. CNC Controller

- Controls the tool on the basis of 4 axes: X, Y, Z & C.
- Uses stepper motors & lead screws for tool movement with minimum step feed of 0.05 μm

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Elements of USMM

5. Micro-tool:

- Tool shape & dimensions of the final product depends on those of the tool.
- Tool should be designed to provide maximum amplitude of vibration at the free end at a given frequency.
- Tool materials should have high wear resistance, good elastic & fatigue strength, optimum values of toughness & hardness.
- Materials used: SS, Brass & Mild steel.

Elements of USMM

6. Abrasive Slurry: consists of abrasive particles + Water/Oil.

- Abrasive concentration: 30-60 % by weight.
- The abrasive slurry is fed to the tool gap.
- The slurry acts as coolant & removes debris from cutting area.
- SiC, Boron Carbide, Aluminium Oxide & Diamond dust are used as abrasives.

Elements of USMM

7. Work piece:

- Materials like Germanium, Ferrites, Glass, Quartz… which exhibit high hardness & brittleness can be successfully machined with USMM.
- As the hardness of material increases, MRR decreases.

Classification of USM

1. Based on slurry system
2. Based on vibration mechanism

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Classification of USM based on slurry system

1. External slurry system 2. Internal slurry system

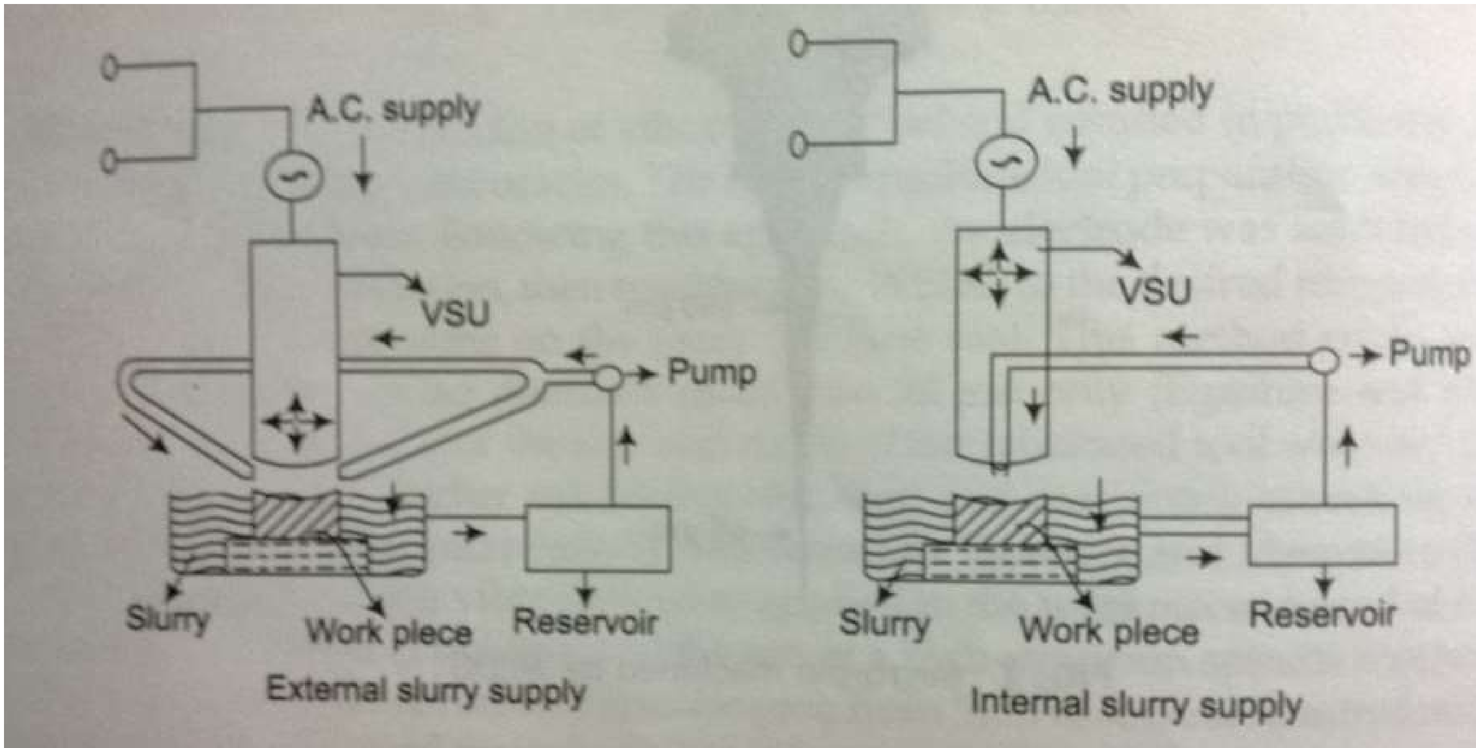

FIG. 8 Slurry System

Classification of USM based on vibration mechanism

1. Ultra sonic vibrations are applied to the tool, while work piece remains stationary.
2. Vibrations are applied to work piece / table, while tool remains stationary.

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Mechanism of material removal in USMM

1. Mechanical abrasion by direct hammering of abrasive particles into work piece. (Kinetic energy)
2. Micro chipping by the impact of freely moving abrasives and soft surface.

Major Reasons

3. Cavitation erosion by abrasive slurry – The entrapped gas is compressed in the gap and forms bubbles – it bursts and causes material removal.
4. Chemical action between slurry and work piece

Minor Reasons

Process Parameters of USMM

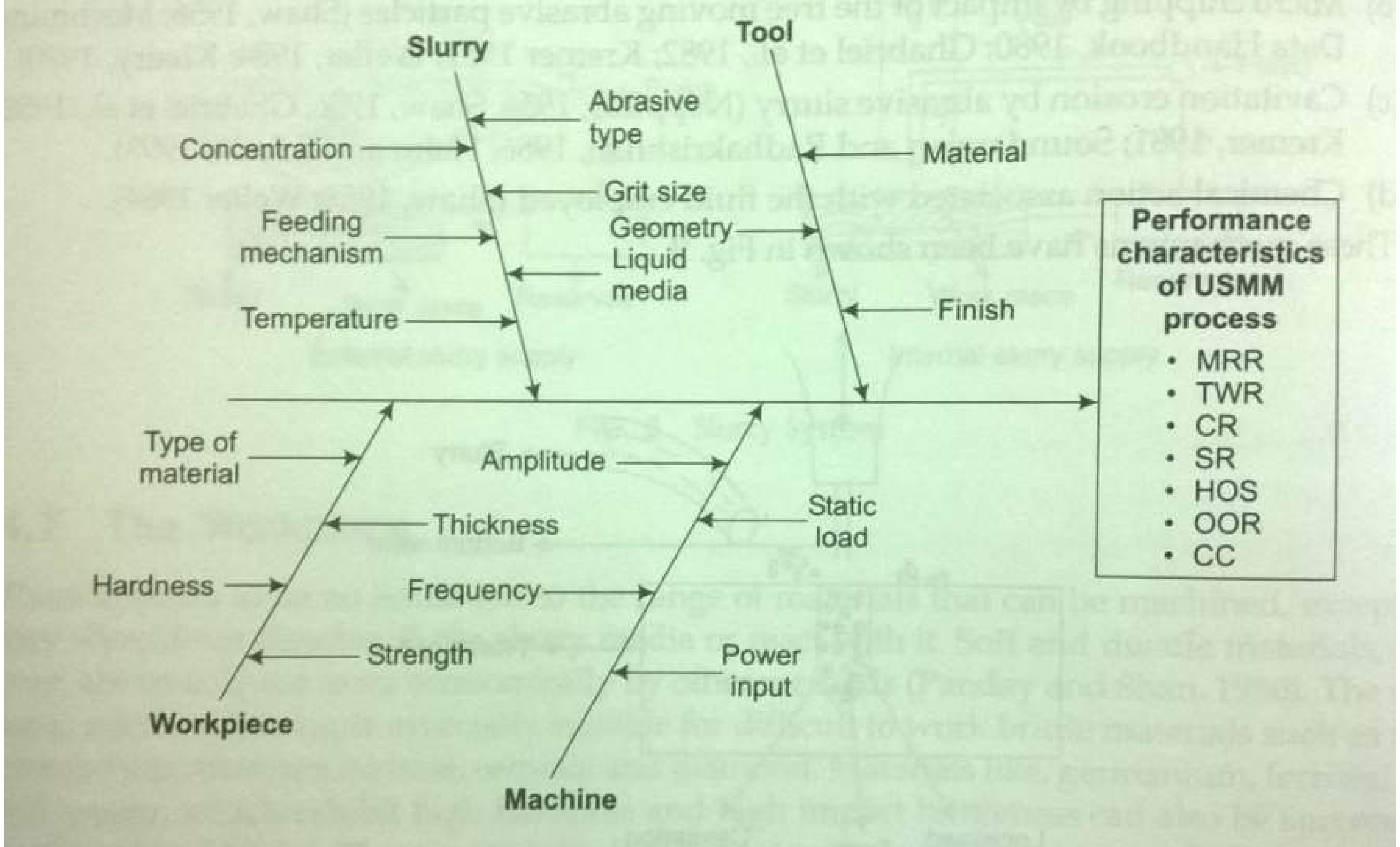

FIG. 10 Cause-Effect Diagram of USMM Process

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Machine based parameters

1. Frequency of ultra sonic oscillations,
2. Amplitude of ultra sonic oscillations,
3. Static load / Power input.
4. Rotary motion of work piece/tool head.

Performance Characteristics

1. Machining Rate,
2. Surface Finish,
3. Machining Accuracy,
4. Tool Wear.

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Performance Characteristics & their evaluation

1. Machining Rate / Material Removal Rate (MRR)

   MRR is evaluated in terms of penetration rate & volume of material removal / unit time.

2. Tool Wear Rate (TWR)

   TWR is calculated by measuring the weight loss of tool in drilling a hole / unit time.

3. Tool Wear Ratio

   Tool wear Ratio is calculated as the ratio of length of tool wear to the depth of the hole drilled.

Performance Characteristics & their evaluation

4. Aspect Ratio

is defined as the ratio of depth to diameter of a hole. As aspect ratio increases, machining becomes challenging.

5. Cutting Ratio (CR)

CR is defined as the material removal rate / unit tool wear. CR should be considered before finalizing work piece – tool combination.

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Performance Characteristics & their evaluation

6. Surface Finish / Roughness

can be evaluated in terms of boundary layer, surface profile & surface roughness measurements.

7. Machining Accuracy is evaluated in terms of

i. Out of Roundness (OOR)
ii. Conicity (CC)
iii. Hole oversize (HOS)

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Effect of process parameters on quality characteristics

- Process Parameters are,

1. Machining Parameters,
2. Abrasive slurry characteristics,
3. Work piece properties,
4. Tool material properties.

- Quality Characteristics are,

1. Material Removal Rate (MRR)
2. Tool Wear
3. Surface Finish
4. Accuracy

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Effect of machining parameters on MRR

- Machining Parameters are,

1. Amplitude of vibrations
2. Frequency of vibrations
3. Static load / Power input
4. Rotary motion of micro tool

Effect of machining parameters on MRR

1. Amplitude of Vibrations : As amplitude of vibrations increases, MRR also increases.
2. Frequency of vibrations: As Frequency of vibrations increases, MRR also increases.
3. Static load / Power input: As static load increases, amplitude & frequency of vibrations increases, so MRR also increases.
4. Rotary motion of tool: Improves MRR & accuracy, reduces cutting force requirement.

Effect of abrasive slurry characteristics on MRR

- Abrasive slurry characteristics are,

1. Concentration of abrasives,
2. Feeding mechanism used,
3. Temperature of slurry,
4. Abrasive type,
5. Grit / Grain size,
6. Liquid media used.

Effect of abrasive slurry characteristics on MRR

1. Concentration of abrasives: Optimum level of concentration of abrasive is 30-40%. Concentration above and below optimum level will reduce MRR.
2. Slurry feeding Mechanism: Internal feed mechanism is found to be more effective compared to gravity feed & external feed mechanisms.
3. Temperature of slurry: As temperature of slurry increases, bond strength of material decreases & cavitation increases, so MRR will also increase.

Effect of abrasive slurry characteristics on MRR…

4. Abrasive type: Hard abrasives removes material more effectively compared to soft ones.
5. Grit / Grain size: As grain size increases, contact area between abrasives & work piece increases, which increases MRR, but reduces surface finish.
6. Liquid media used: The media used should have high density, thermal conductivity & low viscosity. Low viscosity of media enables effective material removal from narrow cavities.

Effect of work piece material properties on MRR

- Fracture toughness & hardness: As fracture toughness & hardness of work piece increases, MRR decreases.
- Brittle materials are more effectively machined compared to ductile materials. This is because as ductility increases, the abrasive particles will get embedded on the work piece rather than ablating it.

Effect of tool material properties & tool geometry on MRR

1. Hardness of tool: As hardness increases, MRR also increases.
2. As cross sectional area of tool reduces, Machining rate increases.

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Effect of machining parameters on TWR

- Two types of tool wear

1. Longitudinal wear
2. Diameter wear

- As amplitude & frequency of vibrations increases, TWR increases.
- As Static load/Power input increases, amplitude & frequency of vibrations will increase, which will in turn increases TWR.
- As machining time & depth of hole increases, TWR also increases.

Effect of abrasive slurry parameters on TWR

1. **Abrasive grain size**: As grain size become coarse, TWR increases.
2. **Hardness of abrasives**: As hardness increases, TWR also increases.

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Effect of work piece material properties on TWR

- Hardness & toughness of work piece: As hardness & toughness of work piece increases, TWR also increases.

Effect of tool material properties on TWR

- As hardness, impact strength & toughness of tool material increases, TWR reduces.

Effect of machining parameters on Surface Finish

- As amplitude of vibrations increases, surface finish reduces.
- As feed rate & depth of cut reduces, surface finish increases.
- Frequency of vibrations has got less effect on surface finish obtained.

Effect of abrasive slurry parameters on Surface Finish

- As abrasive grain size decreases, MRR reduces & surface finish increases.
- As viscosity of slurry increases, surface finish also reduces.

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Effect of work piece properties on Surface Finish

- As brittleness & hardness of work piece increases, surface finish reduces.
- This is because highly brittle materials are susceptible to micro-crack formation, which affects surface finish.

Effect of tool geometry & finish on Surface Finish

- Tool irregularities are reproduced on machined surface.
- So surface finish of the tool surface should be kept higher than the surface finish required on the work piece.

Effect of process parameters on accuracy

Classifications of accuracy

1. Dimensional accuracy (HOS – Hole Over Size)
2. Form accuracy (Out of Roundness (OOR) & Conicity (CC))

- Grain size: As grain size reduces, TWR also reduces which improves accuracy.
- Aspect ratio: As aspect ratio increases, accuracy reduces.
- Brittleness & hardness of work piece: As brittleness increases, due to crack formation, OOR increases.

Effect of process parameters on accuracy

- Tool material used: As fracture toughness & wear resistance of tool increases, accuracy of the machining process also increases.
- Slurry system: Internal slurry system improves accuracy of work.
- Tool shape: Negative tapered tool improves accuracy.

Advantages & Disadvantages of USMM

- USMM can be used for machining hard, brittle and difficult to machine materials like ceramics, quartz, glass etc.
- Best machining rates can be obtained on materials harder than HR 60.
- Lower machining rates & high machining costs are the main disadvantages of USMM.

Process capabilities of USMM

- Micro-hole drilling: Advanced USMM machines are capable of drilling holes as small as 5 μm in diameter & 37 μm depth.
- Aspect ratio of nearly 7 has been achieved for 21μm diameter holes.
- Best tolerance obtained in high end machine is +/- 0.5 μm.
- Maximum surface finish obtained is 0.4 μm Ra
- Accuracy: Lowest reported values of HOS, OOR & CC are 0.2 μm ,1.0 μm & 5% respectively.

Process capabilities of USMM…

- USMM can be effectively used for machining materials like Sintered Alumina, Silicon Carbide & Silicon Nitride whose hardness is more than 1500 Hv.
- Ultra sonic micro-de-burring can be done by USMM within 2.5 to 25 μm tolerance limit.

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Applications of USMM

1. For making tool dies,
2. Parts of wire drawing equipment,
3. Machining watch bearings & gears,
4. Drilling of diamond dies,
5. Aerospace applications,
6. Surgical equipments,
7. Electronics industry.

Module 4

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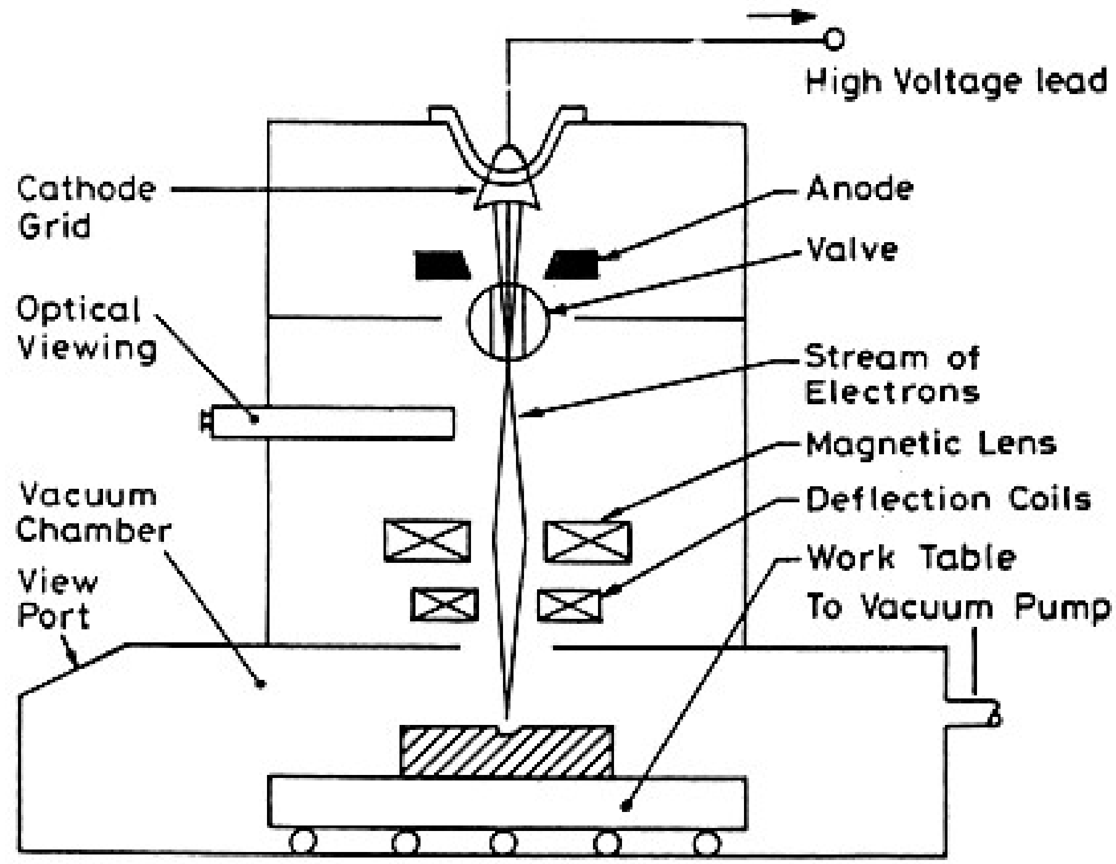
Electron Beam Machining (EBM)



Electron Beam Machining (EBM)

- Electrons are accelerated due to the potential difference between anode and cathode.
- The concave shape of the cathode is intended for concentrating the electron stream through the anode.
- Applied voltage: 50,000 – 200,000 Volts.
- Velocity of electrons: Above 200,000 km/s.
- The valve is used for controlling the beam & duration of machining process.
- An electromagnetic lens is used for reducing the diameter of beam to as small as 25 μm.
- The deflection coils are used to control the electron beam movement.

Material Removal Mechanism in Electron Beam Drilling

- In EB drilling, energy is created & precisely focused on the work piece to bring about highly localized melting.
- On impinging the surface, the kinetic energy of the electrons is converted into thermal energy of high density, which melts and vaporizes the material in a local area.

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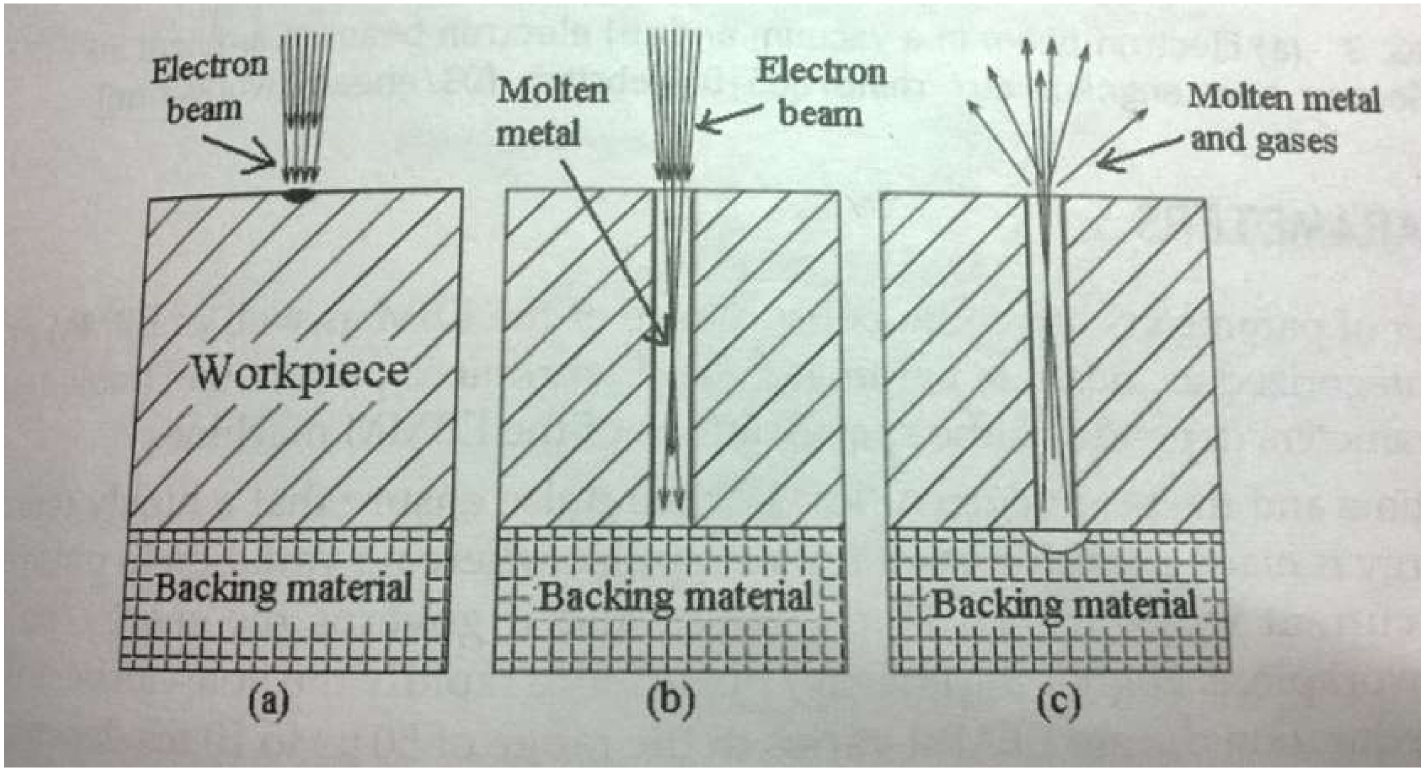
Material Removal Mechanism in Electron Beam Drilling



Material Removal Mechanism in Electron Beam Drilling

- As the depth of cut increases, the beam gets in the way of the molten metal, preventing it from escaping out of the hole.
- To expel the molten material, a backing material is applied to the reverse side of the work piece material being drilled.
- When the electron beam breaks through the work piece material, the backing material reacts to the beam by producing large volume of gas that expands explosively, which removes the molten metal.

Importance of vacuum in EBMM

- The air molecules can adversely interact with the beam of electrons.
- The collision between the electrons and air molecules causes the electrons to veer/change its direction.
- These deviated electrons will hit the un indented areas on the work piece, which will affect the accuracy of the work.
- Atmospheric oxygen will readily react with molten metal to form metal oxides. To avoid formation of oxides, vacuum is important during EBMM.

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Importance of vacuum in EBMM

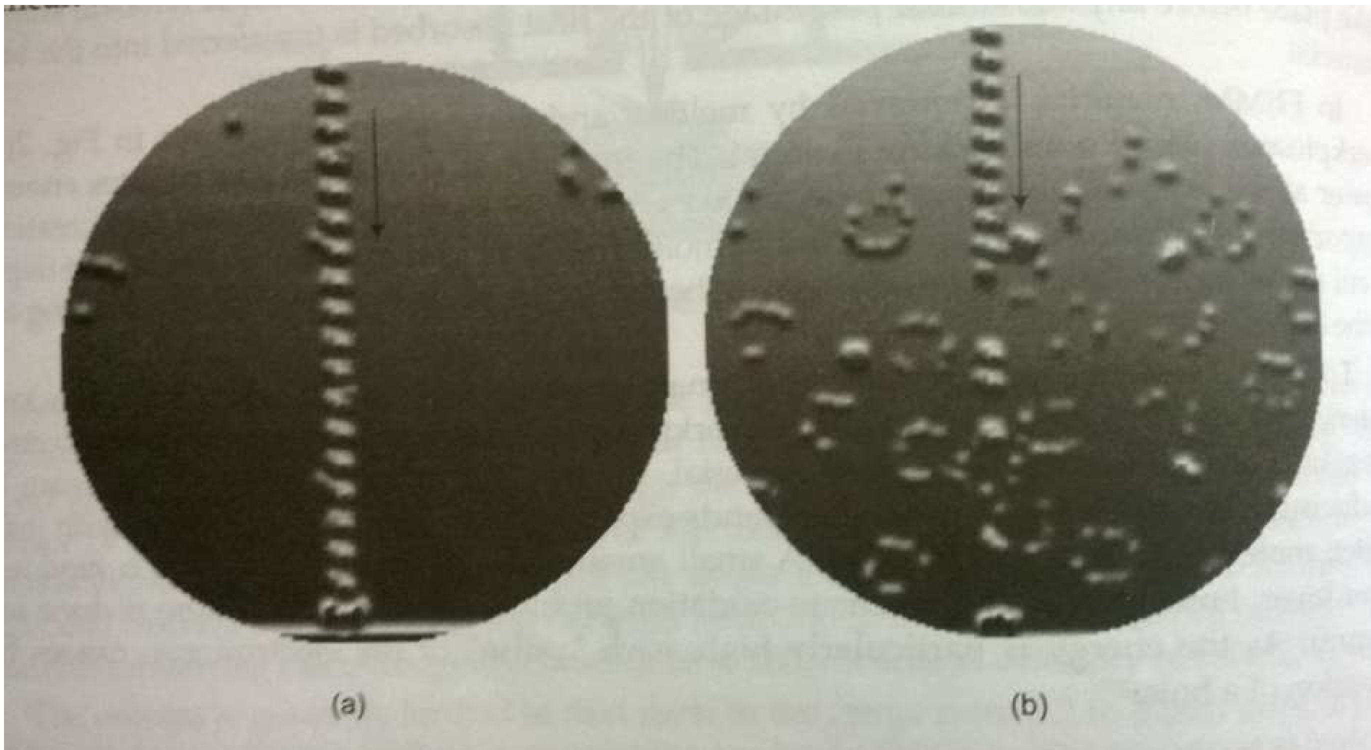

FIG. 3 (a) Electron-beam in a vacuum and (b) electron beam in ambient air

Process parameters

1. Machine based parameters
2. Work piece parameters

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Machine based parameters

1. Pulse duration
2. Beam current
3. Working distance
4. Roundness of beam
5. Consistency of beam diameter
6. Symmetry of focusing lens
7. Vacuum system
8. Movement of work piece.

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Work piece parameters

1. Melting temperature
2. Vaporization temperature
3. Thermal conductivity
4. Thermal diffusivity

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Effect of cutting speed

- To minimize thermal diffusion problem, the beam should be rapidly scanned across the surface to be machined.
- As cutting speed increases, problems due to thermal diffusion & HAZ reduces.

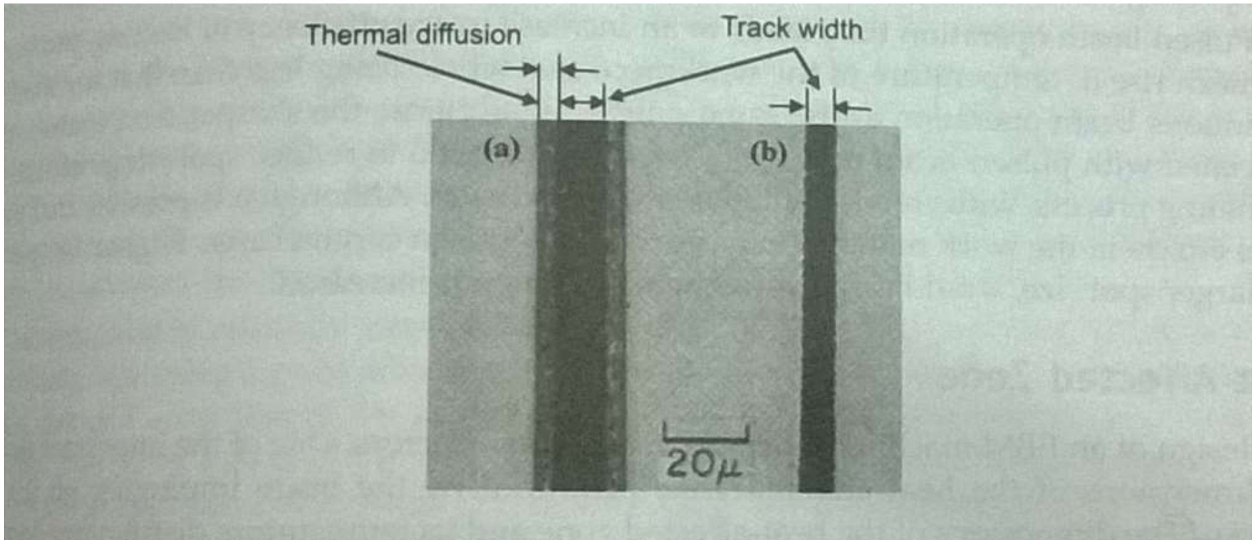

FIG. 4 Cuts in Ta showing variations of track width due to (a) normal cutting speed (b) 3 times higher cutting speed than (a)

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Power Retention Factor

- During the machining process, some of the electrons may ultimately be scattered out of the target.
- Scattering of electrons causes loss of residual energy & reduction in efficiency.
- The fraction of incident energy retained by the work material is termed as power retention factor.

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Conduction losses & temperature rise

- Conduction of heat away from the irradiated spot is the main cause of loss of efficiency during EBMM.
- Peak temperature attained by the work piece is directly proportional to the beam power & inversely proportional to the beam diameter.

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Pulsed Beam Operation

- To reduce the effect of conduction loss, pulsed beam should be used instead of continuous stream of electrons.
- During pulsed beam operation, the focused spot is heated to high temperature before conduction of heat takes place.
- Due to the reduced heat conduction loss, the efficiency of the process is improved & HAZ is reduced.

Heat Affected Zone (HAZ)

- The dimensions of the heat affected zone depends on

1. Energy of incident electrons,
2. Beam current,
3. Diameter of the focused spot,
4. Work piece properties,
5. Pulse duration.

Cross sectional area of electron beam

- The basic requirements to produce electron beam with high energy & small cross sectional area are,

1. An electron gun: To produce a high power electron beam,
2. A focusing system: To reduce beam diameter to improve beam density,
3. A vacuum system: To avoid veer of electrons to improve accuracy.

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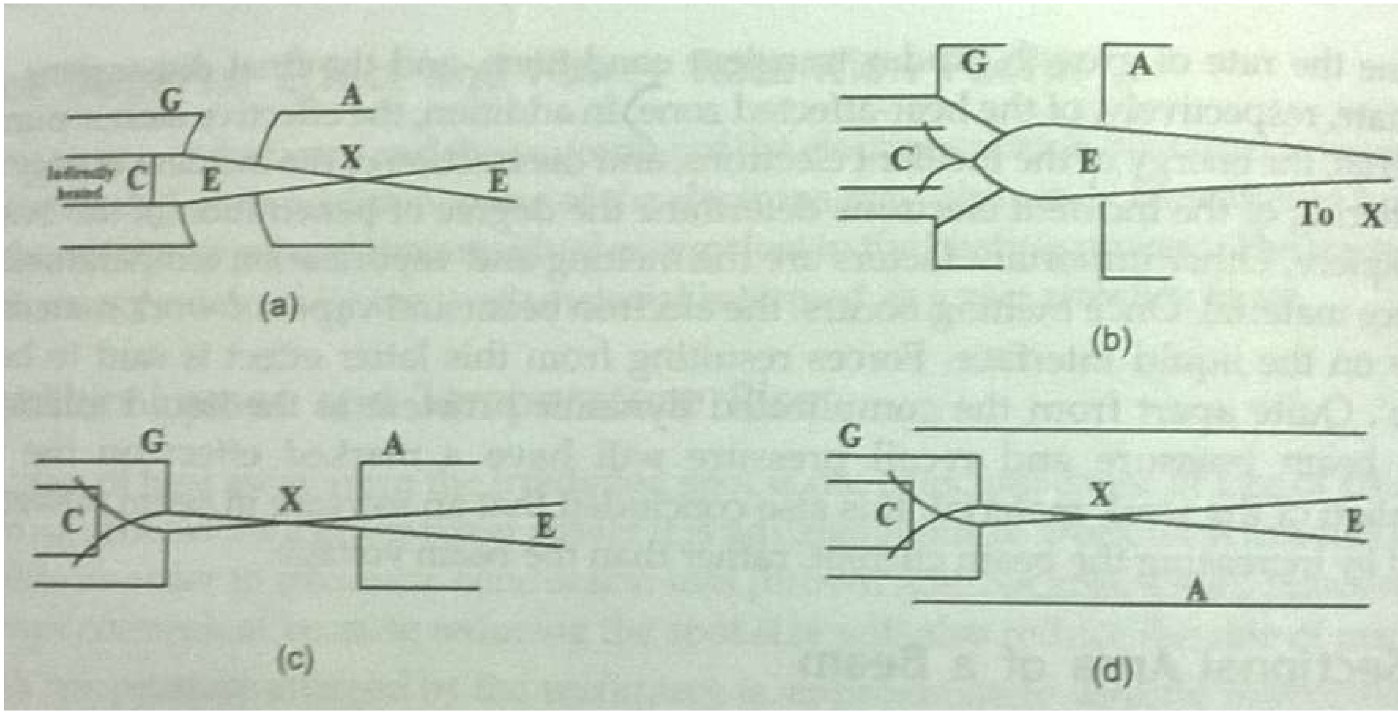
Schematic diagrams of electron guns



(a) Pierce gun configuration, (b) Steigerwald gun configuration, (c) Closed anode normal triode system, (d) Open anode normal triode system.

A – Anode, C – Cathode, G – Grid, E – Electron gun, X – Crossover spot

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Theoretical aspects of electron beam

1. Maximum current density
2. Maximum current in the image/spot
3. Energy transfer to the work piece
4. Material Removal Rate (MRR)

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Theoretical aspects of electron beam

1. Maximum current density

$$j = j_c\left(\frac{qV}{kT}\right)\alpha^2$$

jc = Current density, q = Charge of electron, V = Voltage applied,
k= Boltzmann's constant, T = Cathode temperature in K,
α = Maximum semi angle.

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Theoretical aspects of electron beam

2. Maximum current in the image/spot.

$$I = j_c\left(\frac{qV}{kT}\right)\alpha^2 \times \frac{\pi}{4} d_0^2$$

Where, jc = Current density, q = Charge of electron, V = Voltage applied,
k= Boltzmann's constant, T = Cathode temperature in K,
α = Maximum semi angle, do = Diameter of focused image.

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Theoretical aspects of electron beam

3. Energy transfer to the work piece

$$\theta_0 = 0.033\, j_c \left(\frac{q}{kT}\right) \frac{1}{K C_s^{\frac{2}{3}}} V^2 d^{\frac{5}{3}}$$

Where, Θo = Peak temperature, jc = Current density, q = Charge of electron,
V = Voltage applied, k= Boltzmann's constant,
T = Cathode temperature in K,
K = Thermal conductivity of the material, Cs = Objective lens constant,
d= Diameter of focused image.

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Theoretical aspects of electron beam

4. Material Removal Rate (MRR)

$$MRR = \eta \frac{P}{W}$$

Where, η = Cutting Efficiency, P = Power (J/s), W = Specific Energy (J/cm3)

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Applications of EBM

1. Electron Beam Drilling

- Precision: +/- 25 μm, Accuracy: +/- 12.7 μm, Aspect Ratio 25:1

2. For making fine gas orifices in nuclear reactors,
3. Holes in wire drawing dies,
4. Cooling holes in turbine blades.

Advantages & Disadvantages of EBM

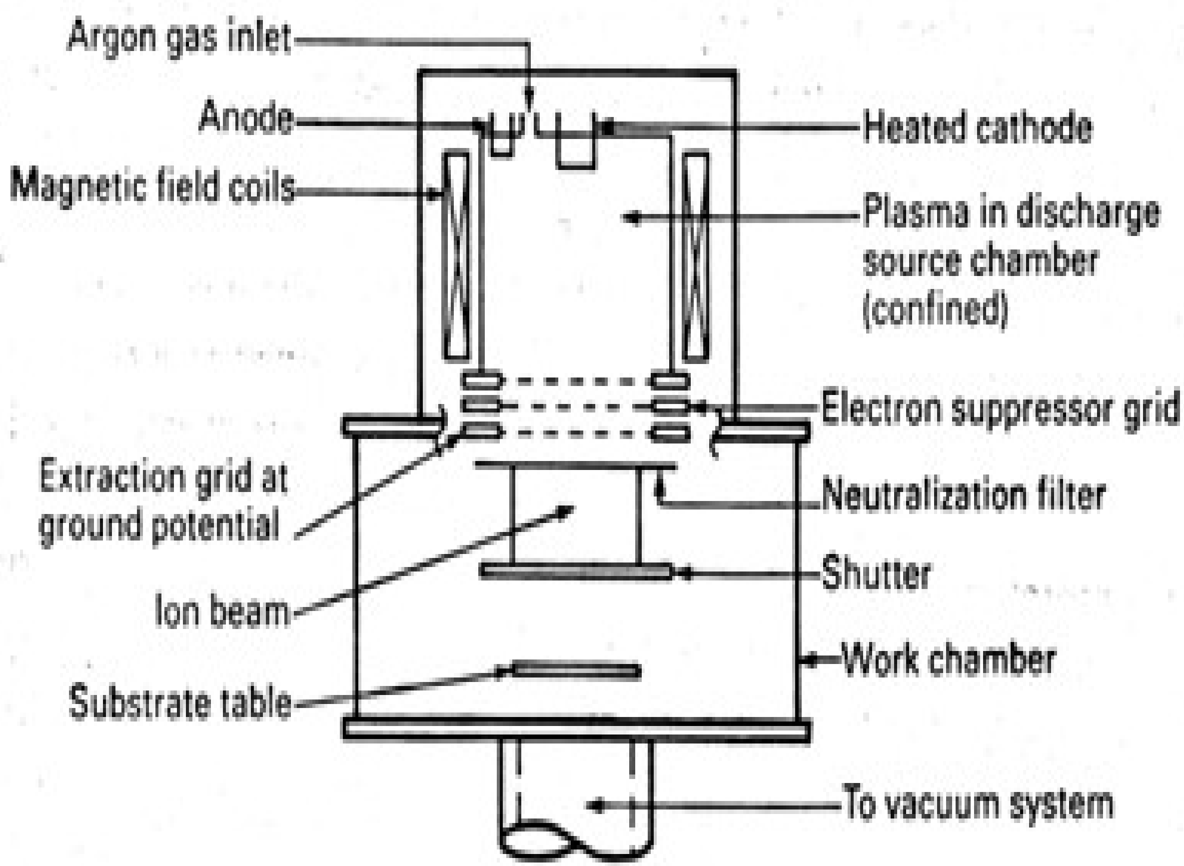
- Advantages:

1. Non-contact type thermal tool,
2. High aspect ratio is attained (25:1) even at inclined angle,
3. Parameters can be easily adjusted.
4. Can produce holes ranging from 6 μm – 1.0 mm

- Disadvantages:

1. Size of vacuum chamber limits the size of work piece.
2. High initial investment & running cost,
3. Skilled programmer & labor is required.

Focused Ion Beam Machining (FIB)
Equipment



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Plasma Source in IBM

- A heated element usually tungsten acts as cathode, from which electrons are accelerated by means of high voltage (above 1 kv) towards anode.
- During the passage of electrons from the cathode to the anode, they interact with argon atoms and the following reaction takes place.

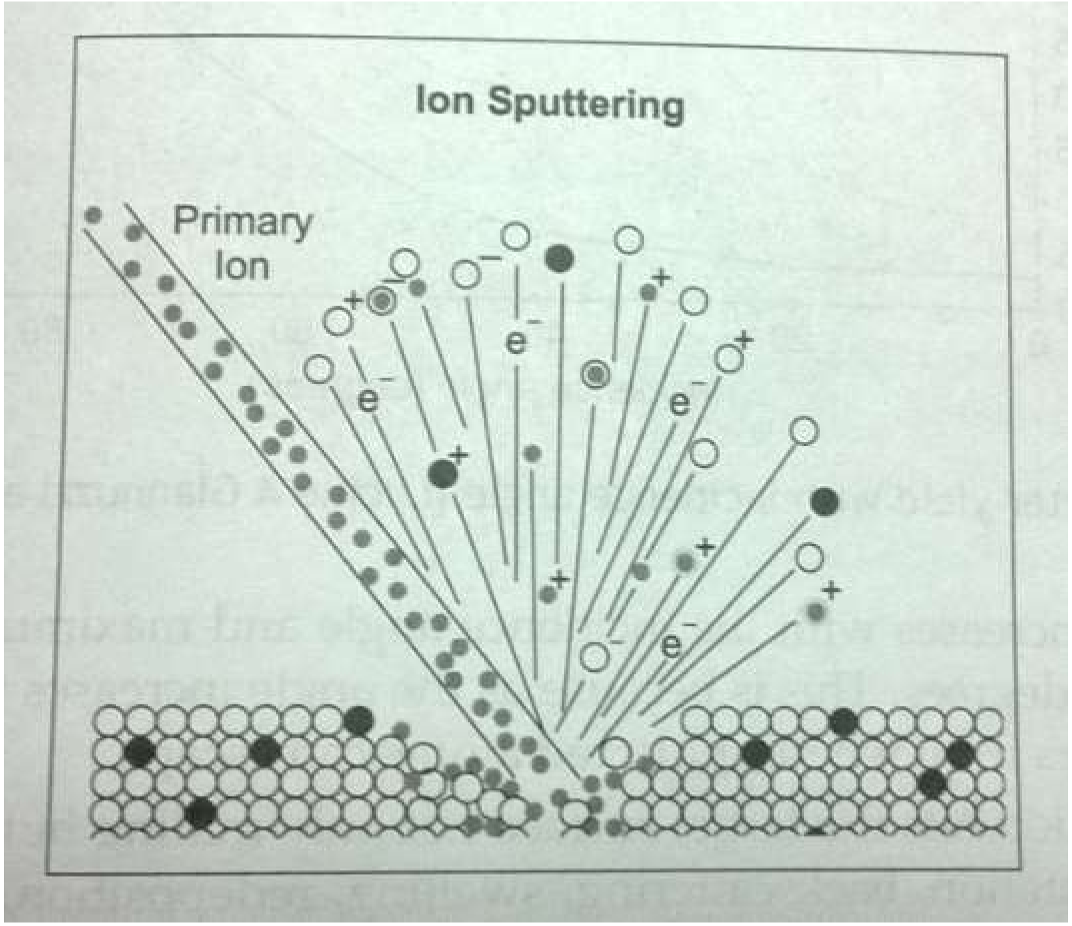
  $Ar + e^- = Ar^+ + 2e^-$ (Argon ions produced)

- A magnetic field, obtained from an electromagnetic coil or a permanent magnet, is applied between the anode and cathode.
- It make electron spiral which increases the path length of the electrons and ionization.

Interaction of ion with substrate

- Compared to electrons, ions are 20 times larger in size & 130 times heavier in mass.
- Due to this, ions removes material more effectively.
- The removal of atoms from the work piece by the accelerated ions is a physical sputtering process.
- Atoms will be removed from the work piece when the energy transferred from the ions is more than the binding energy of atoms.
- The sputtering yield (No. of atoms ejected / ion) is in the range of 1-50.

Ion Sputtering



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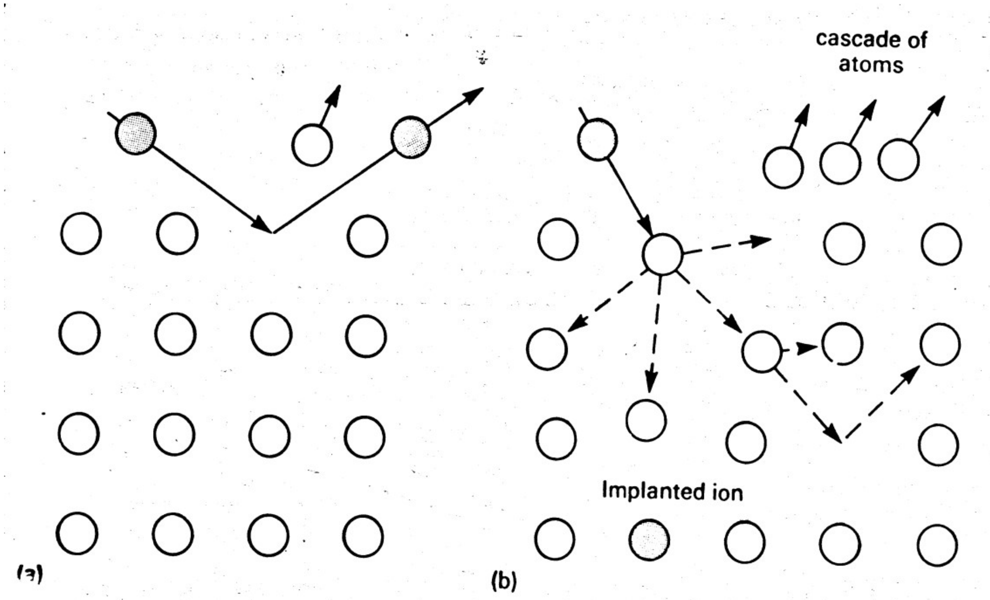
Collision Cascade / Cascade of atoms

- When a target atom is dislodged from its position by the accelerated ion, it can contribute to further removal of atoms, by way of transferring its momentum. This phenomenon is termed as collision cascade.



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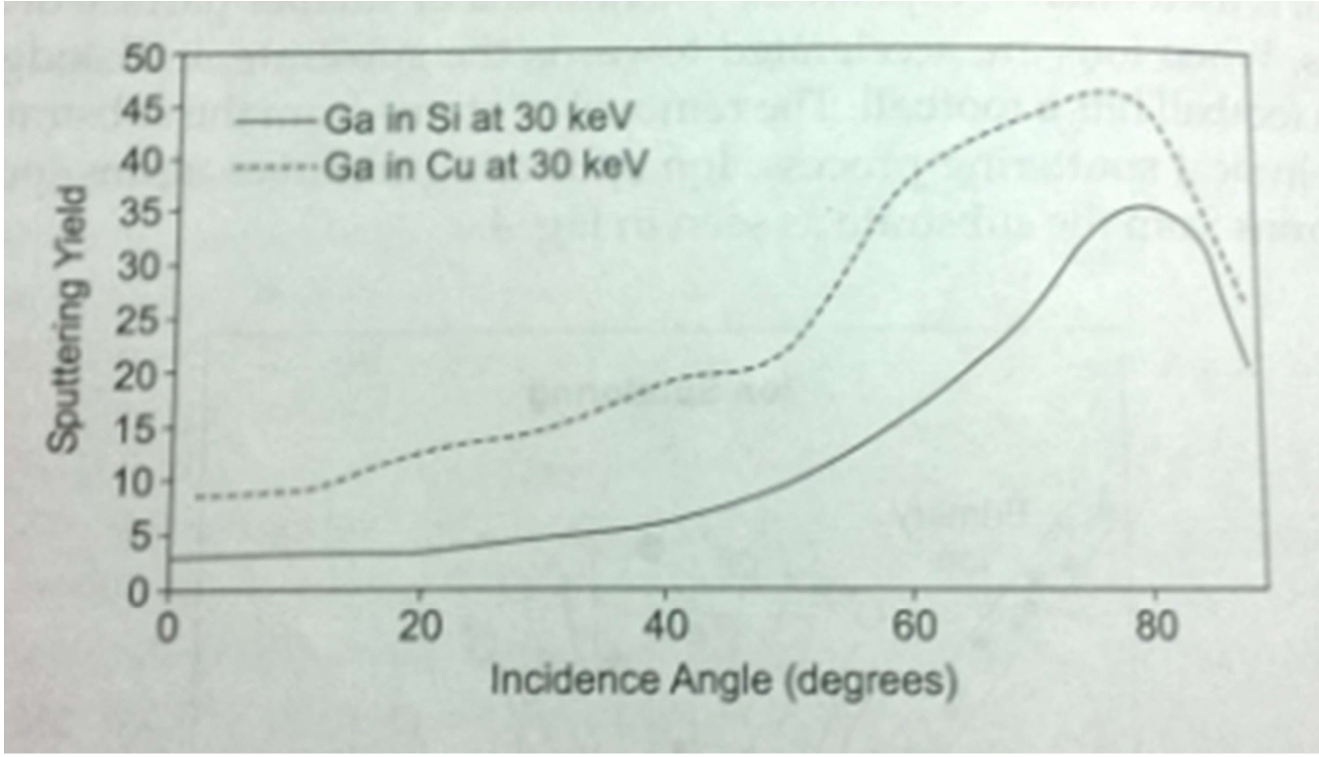
Sputtering Yield Vs Incidence Angle

- Sputtering Yield is maximum when Incident Angle is 60-90 Deg



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Imaging with FIB System

- Images can be obtained by using either

1. Scanning Electron Microscope (SEM),
2. Ion beam imaging.

- An advanced two-beam system combines the non-destructive images of SEM with the milling capabilities of FIB.

FIB Milling

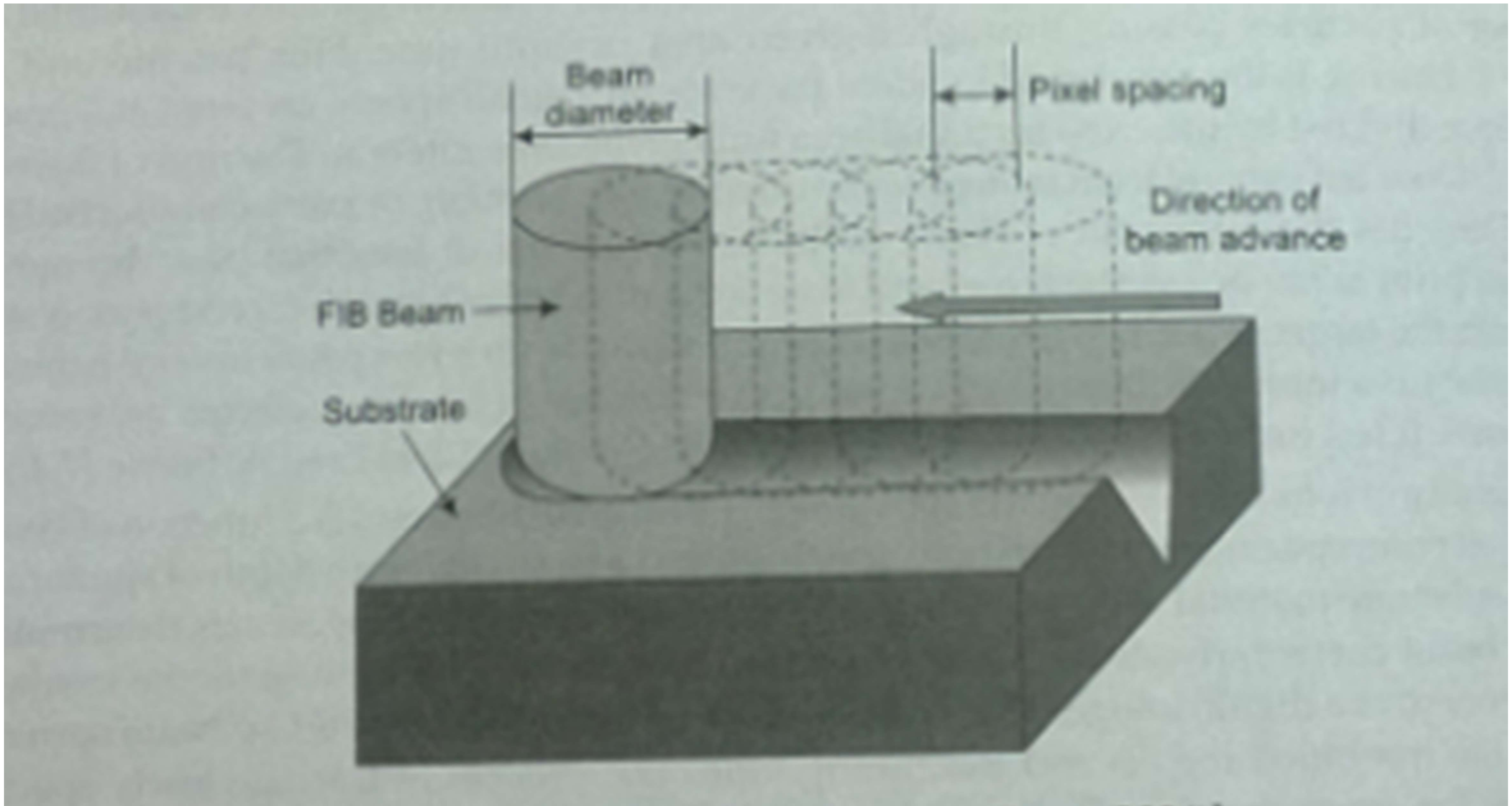

FIG. 7 FIB milling [Ampere A Tseng (2004)]

FIB Milling – Process Parameters

1. Scan rate – As speed increases, MRR reduces.
2. Beam spot size
3. Dwell time (Duration for which beam rests on each pixel)
4. Degree of overlap

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Rectangular Raster Scan Vs Line Scan

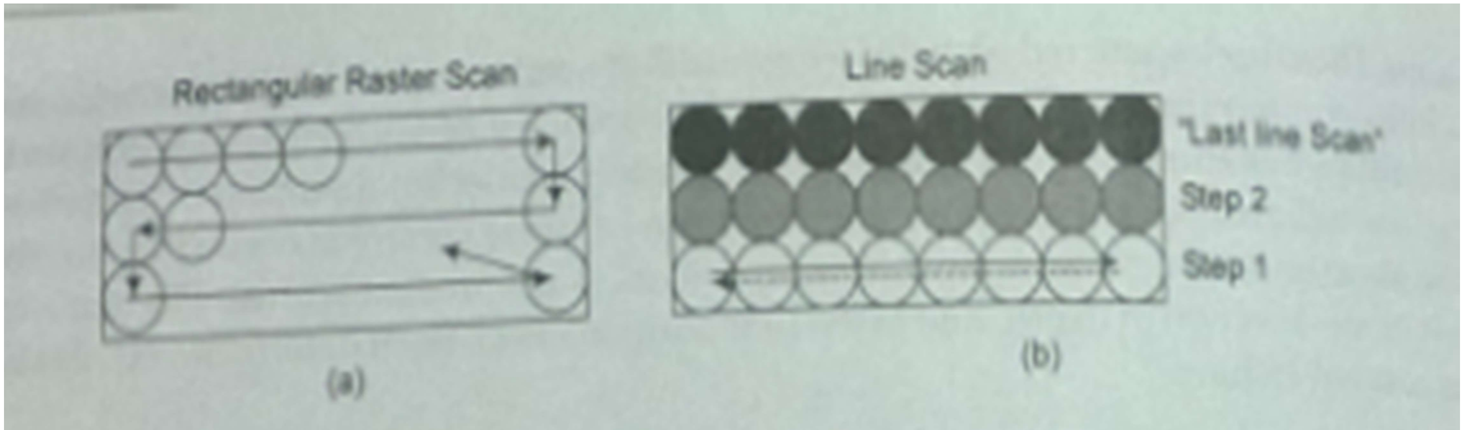

FIG. 6 Scanning of a rectangular pattern

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Gas assisted FIB processing

- Gases are used for enhanced milling and deposition of metals.
- Precursor gas containing the element to be deposited is passed through a capillary gas feeding nozzle towards the substrate.

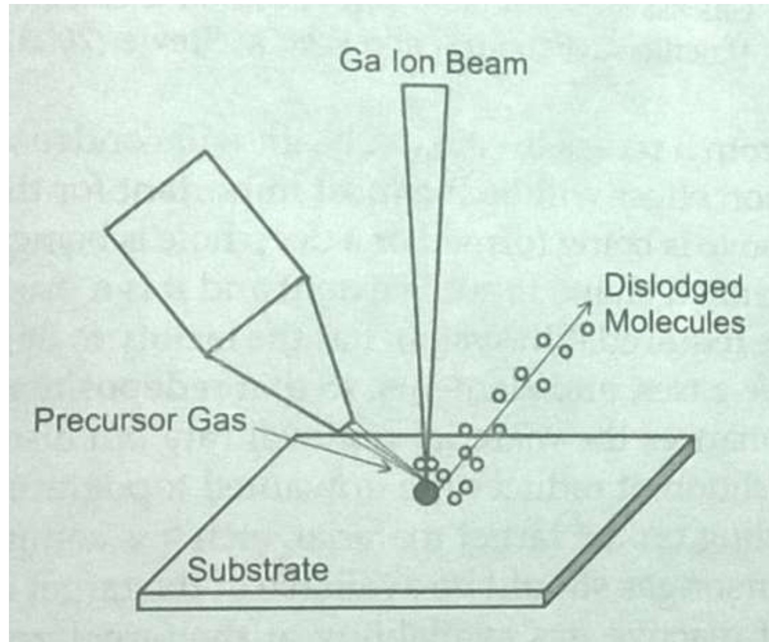

FIG. 9 Gas assisted FIB deposition

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Precursor gases used for FIB deposition

Element to be deposited	Precursor gas used
Carbon	Phenanthrene
Platinum	Tri methyl cyclo penta dienyl platinum
Tungsten	Tungsten hexa carbonyl
SiO_2	Oxygen + Tetra methoxysilane
Aluminium	Trimethylamine alane

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Applications of FIB Machining

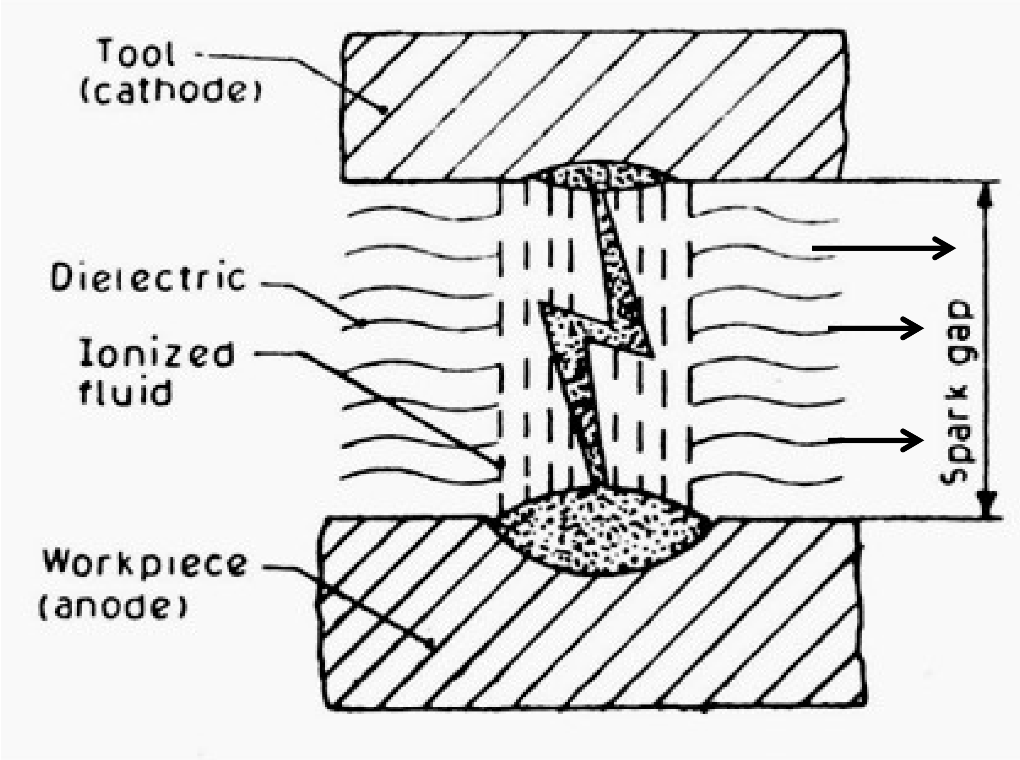
1. Fabrication of lathe tools for nano machining,
2. End mill cutters for micro machining,
3. Micro surgical tools,
4. Fabrication of diamond micro indenters,
5. Tools and dies for micro forming,
6. Tools and dies for Micro EDM,
7. Diamond and silicon nitride mould for nano patterns.

Applications of FIB Machining

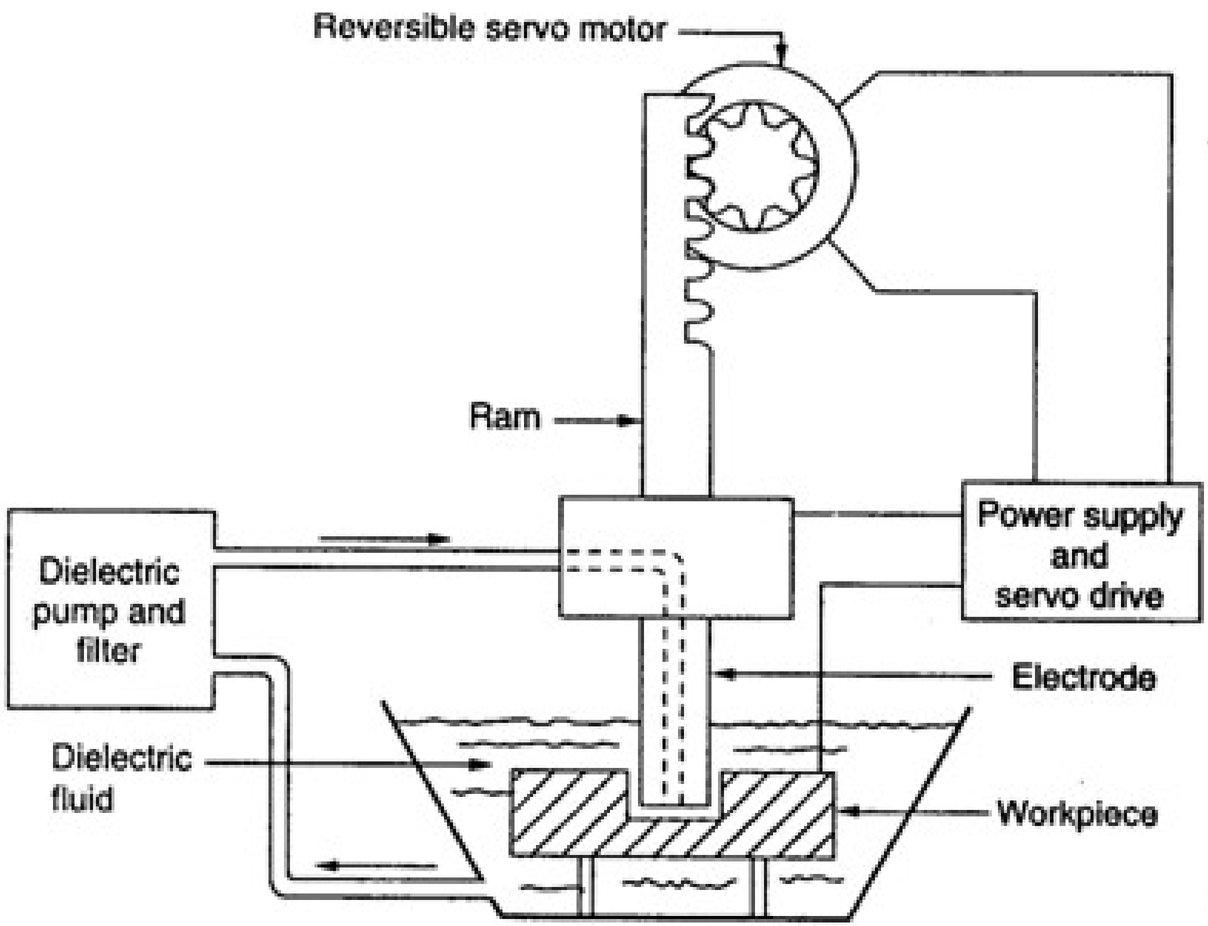
- **Smoothing** – Smoothing of mirrors and for modifying the thickness of thin films without affecting surface finish.
- **Ion Beam Texturing** – For texturing surfaces of the materials like nickel, copper, stainless steel, silver, gold etc.
- **Ion beam cleaning** – Used for cleaning surfaces which are produced by EBM, EDM etc.
- **Shaping, Polishing and Thinning** – Argon ions has been used to enhance polishing, macroscopic thinning and shaping of thin materials
- **Ion Milling** – Ion milling is useful for the accurate production of shallow grooves by milling through masks to produce regular arrays of pits with widths 5 – 200 μm and depths upto 1mm. Some researchers reported that ion milling is an alternative for chemical etching of devices of fine geometry.

Module 5

Electric Discharge Machining (EDM)
Working Principle



Micro EDM - Setup



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Micro Electric Discharge Machining (MEDM)

- Working principle is same as that of EDM
- CNC controlled
- Tool movement controlled by servo mechanism
- Positional accuracy: +/- 0.5 μm

Pulse Characteristics

- Energy of a pulse:

$$\mathbf{E = VIT}$$

Where, V = Voltage, I = Current, T = Time.

- Energy of pulse with ON/OFF times:

$$\mathbf{E = V_p I_p\ ((t_{on}/(t_{on} + t_{off}))}$$

Where, V_p & I_p are Voltage and Current of a single pulse, t_{on} = Pulse ON time, t_{off} = Pulse OFF time.

Material Removal Rate (MRR)

$$\text{MRR} = \boldsymbol{\alpha}\, \mathbf{V_p I_p} \left(\left(\mathbf{t_{on}} / \left(\mathbf{t_{on}} + \mathbf{t_{off}}\right)\right)\right)$$

- Where, α = Material removal constant of the work piece.

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Process Parameters of MEDM

- Electrode/ Work piece based parameters

1. Diameter of electrode
   - (As diameter of tool increases, peak temperature attained reduces)
2. Material Hardness
   - (As work piece material hardness increases, MRR reduces)
3. Melting point
   - (As melting point of specimen increases, MRR reduces)
4. Thermal diffusivity
   - (As thermal diffusivity of work piece increases, heat energy utilized for ablation reduces which reduces MRR)

Process Parameters of MEDM

- Dielectric fluid & flushing based parameters:

1. Specific resistance of the fluid
2. Pressure of fluid
3. Contamination
4. Flow rate
5. Supply method

   i) Internal type (Recommended)

   ii) External type

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Process Parameters of MEDM

- Processing / Machining Parameters:

1. Voltage applied
2. Polarity
3. T_{on} & T_{off}
4. Spark gap
5. Electrode rotation

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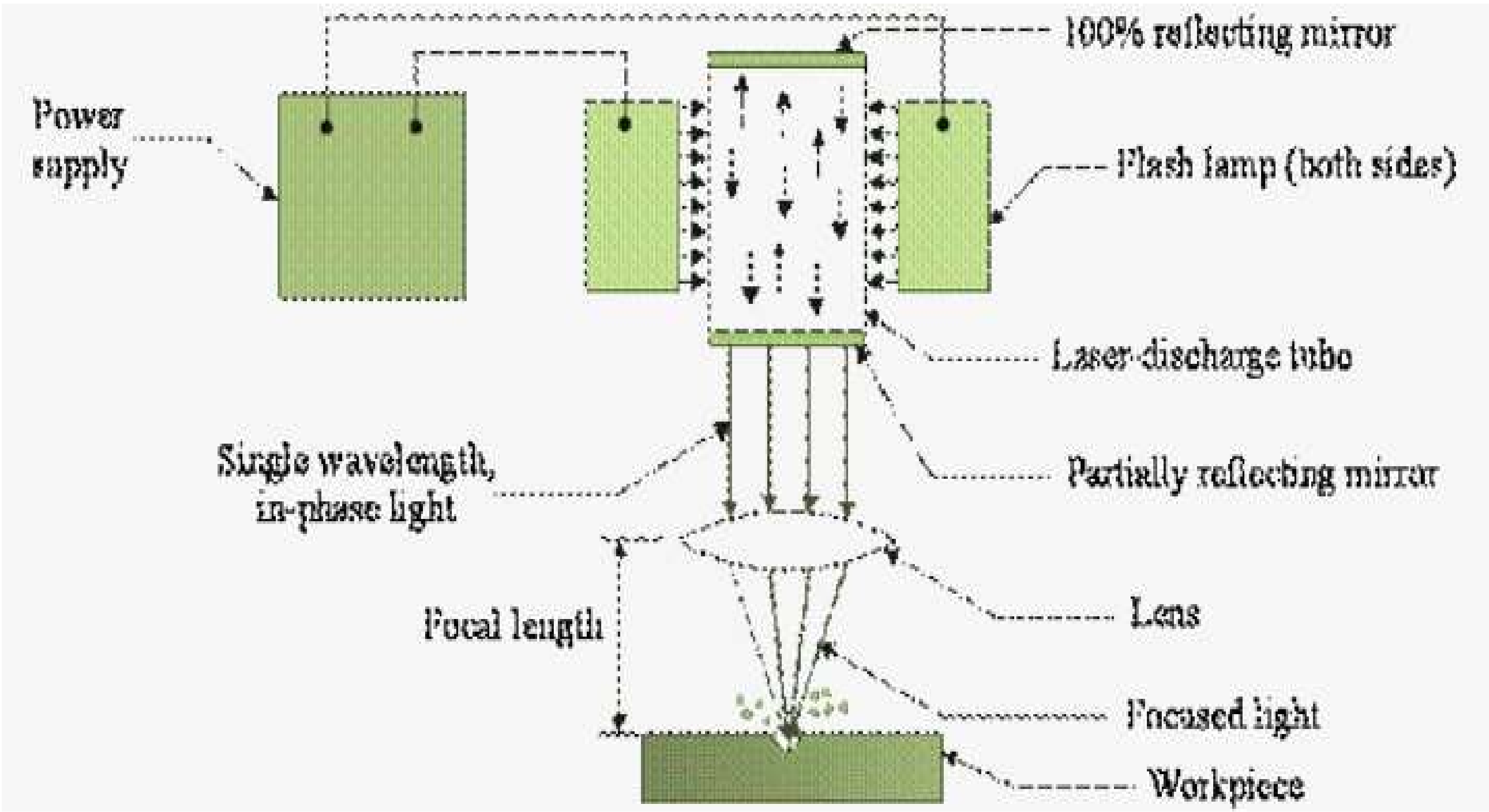
Fabrication of high aspect ratio holes

- Negative polarity to work piece increases accuracy & reduces hole over size (HOS)
- HOS increases with increase in voltage.
- Electrode rotation (Max. speed 50 rpm) improves debris removal & accuracy.
- Horizontal spindle configuration improves debris removal.
- Planetary motion of the electrode improves accuracy as it provides extra space for the removal of air bubbles & debris.
- The maximum machined depth is attained when the gap control speed is 0.01 - 0.02 mm/sec.

Heat Affected Zone (HAZ) in MEDM

- Compared to other non conventional process, MEDM produces less damage & HAZ.
- The HAZ of Micro EDM comprises of region of low hardness.
- Grain size & structure of material around the machined spot hardly changes.
- No recast layer is formed on the surface machined by MEDM.

Laser Beam Machining (LBM)



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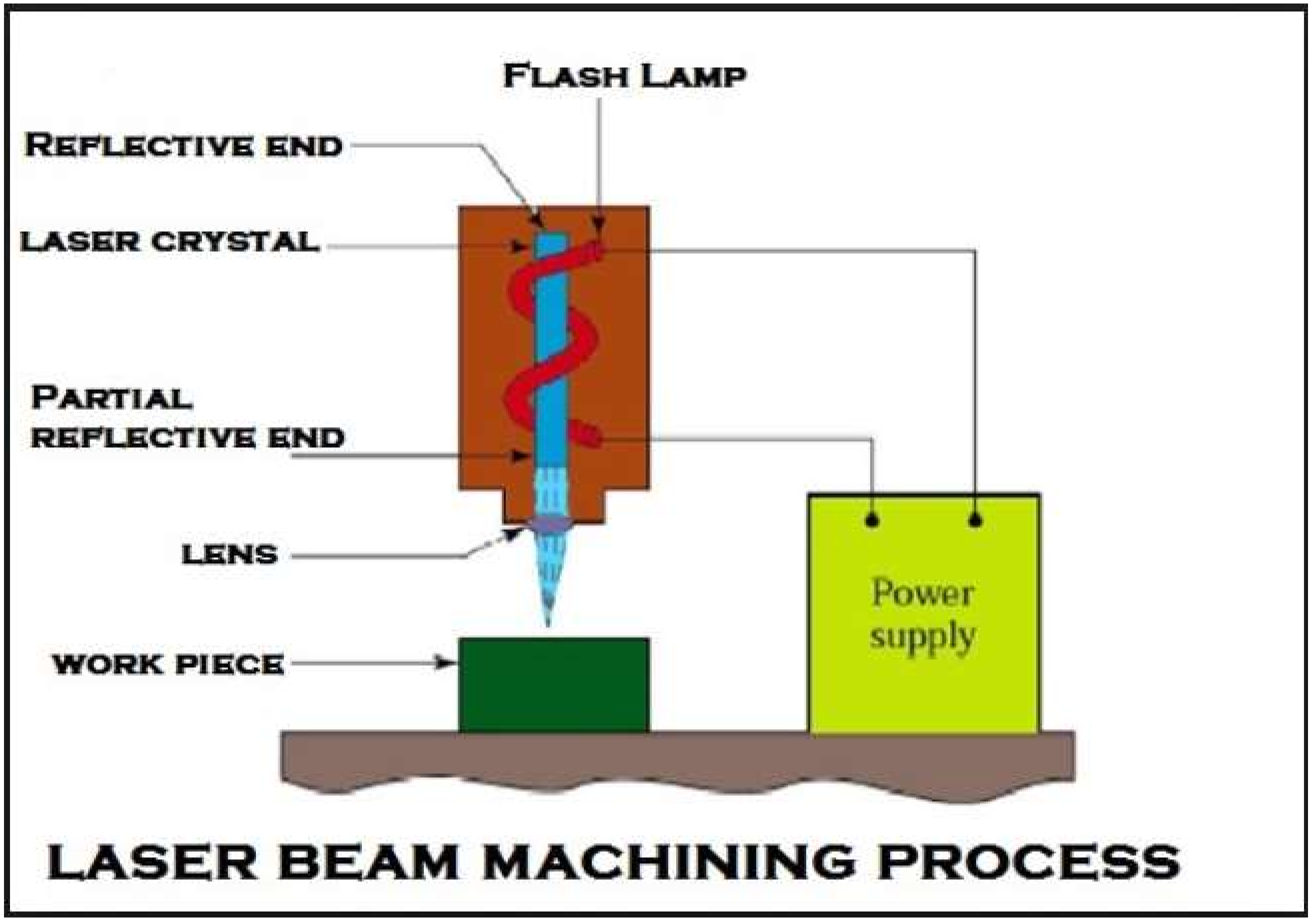
LBM



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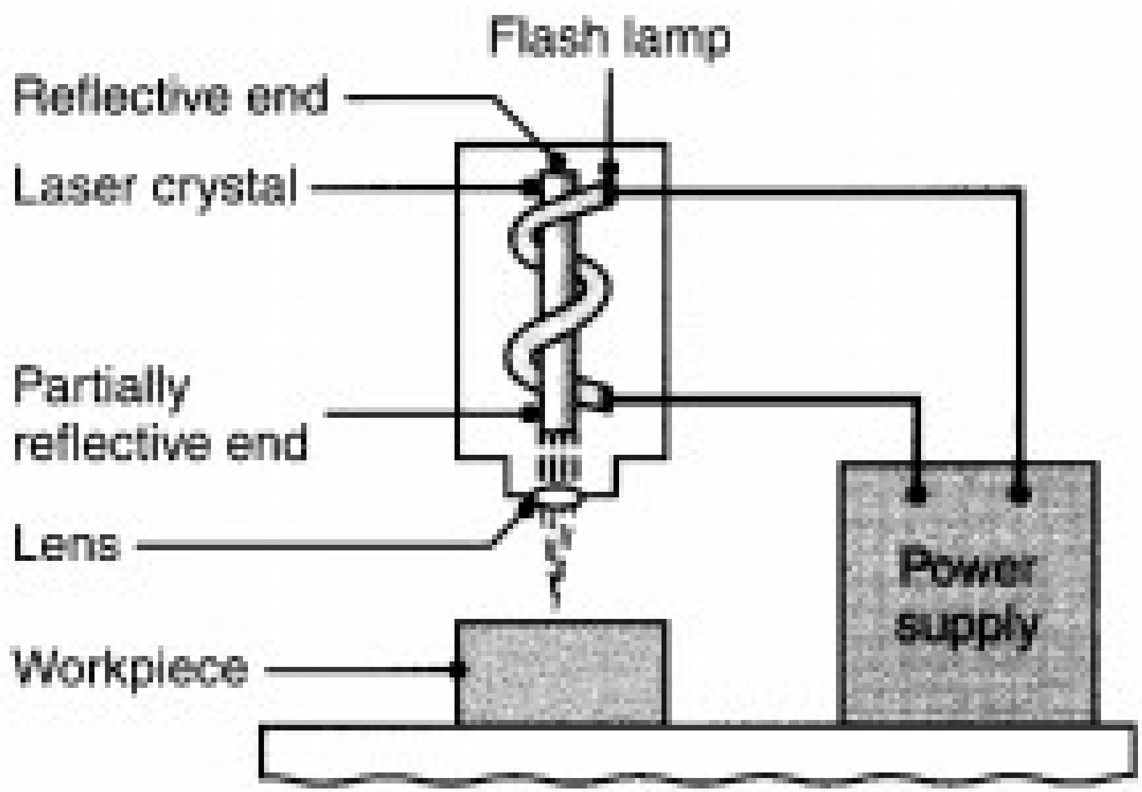
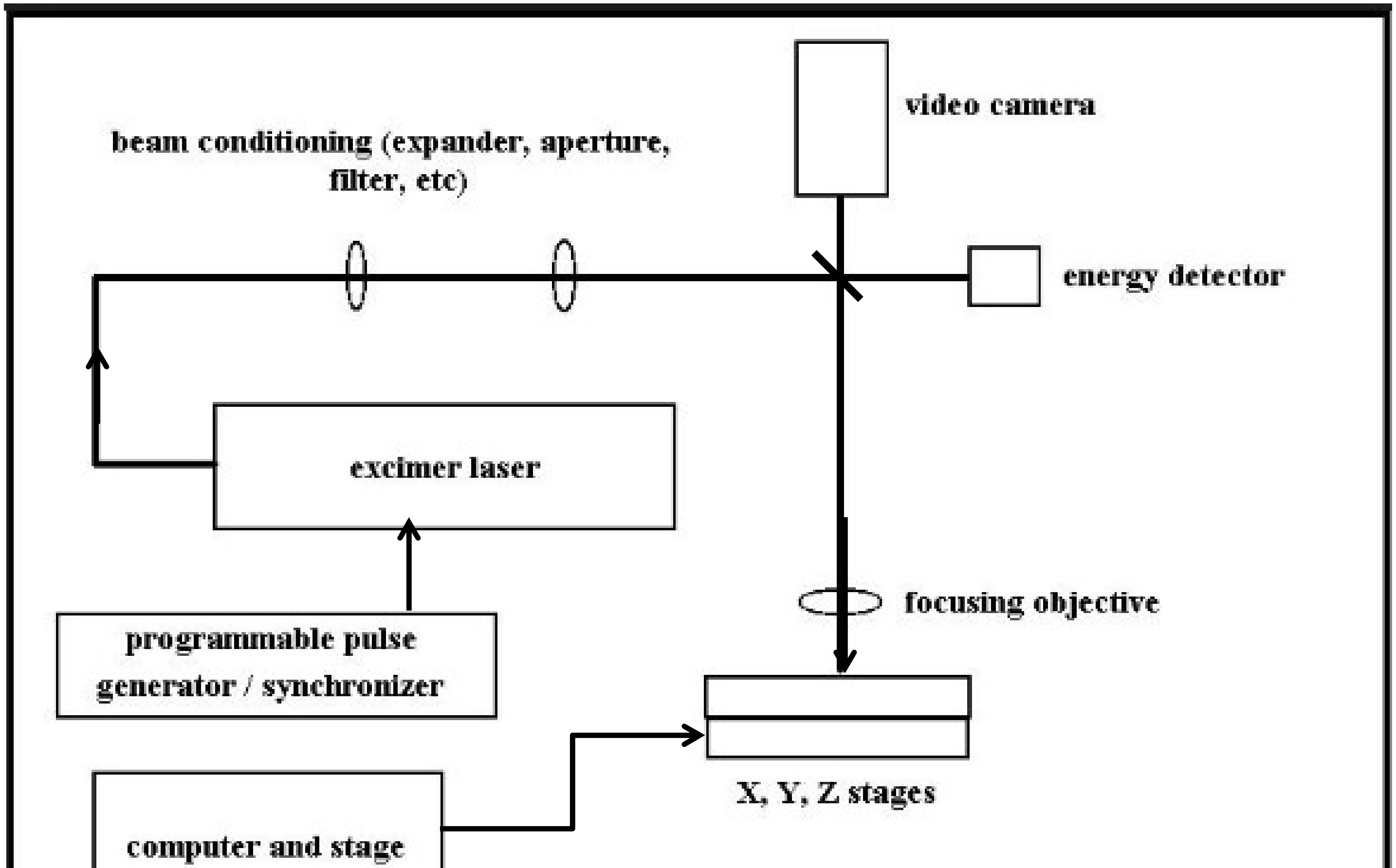
LBM



Flash lamp
Reflective end
Laser crystal
Partially reflective end
Lens
Workpiece
Power supply

Laser Micromachining System



Schematic layout of a laser micromachining system for ablation and/or polymerization.

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Why Laser…?

1. **Directional** - This refers to light divergence over long distances. A laser is collimated and will travel long distances without the beam spreading .

2. **Monochromatic** - Monochromatic means single colour - Lasers emits light that consists of a very narrow spectral range.

3. **Coherent** - All of the light waves emitted by a laser are in phase with each other. All the peaks and valleys are perfectly in line with each other.

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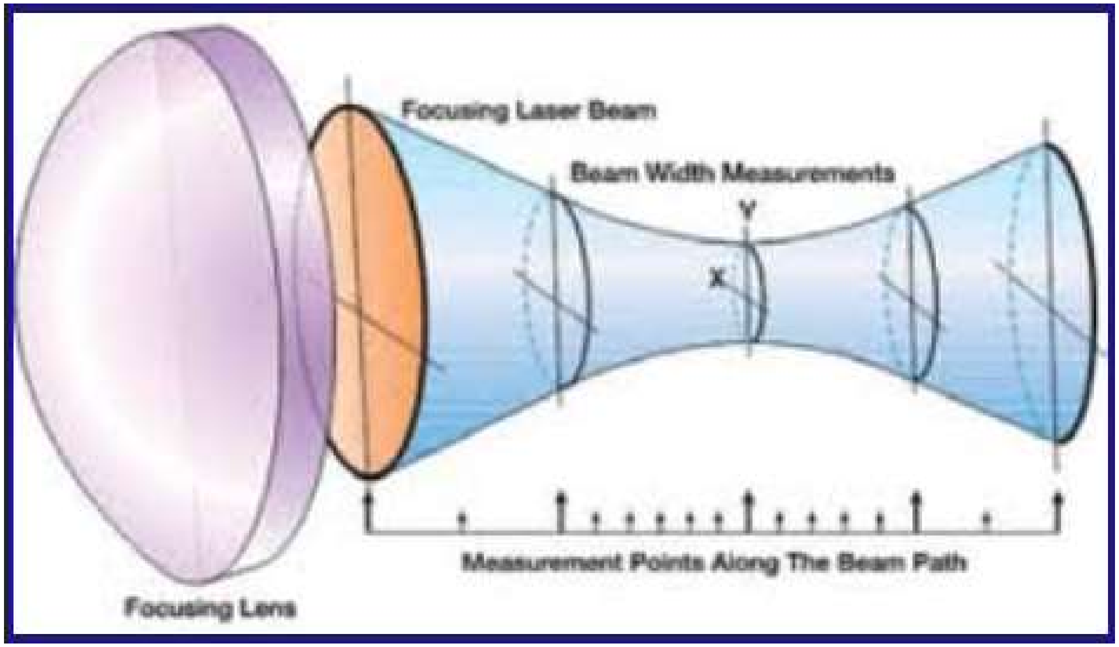
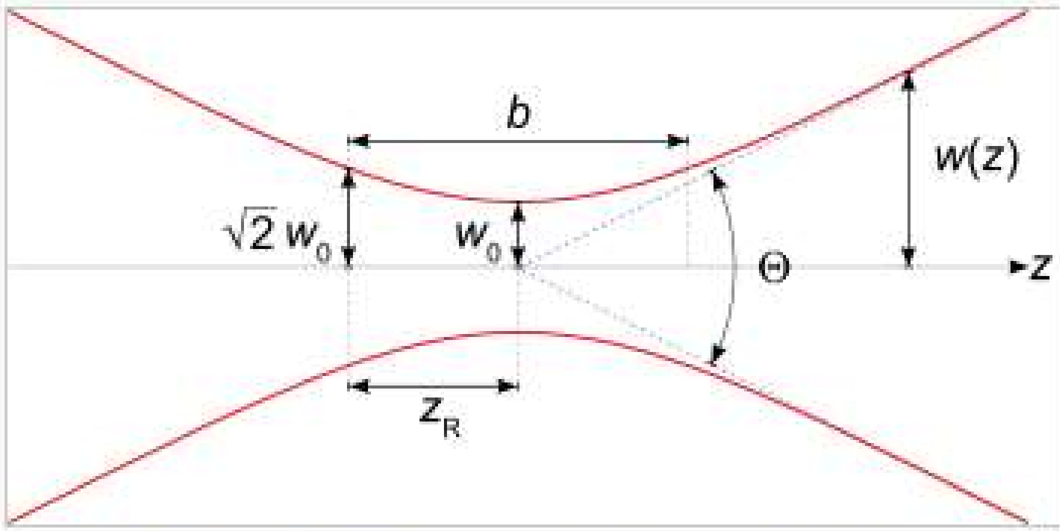
Laser Beam Characteristics
(Gaussian beam)



Laser Beam Characteristics
(Gaussian beam)



Gaussian beam width $w(z)$ as a function of the distance z along the beam. w_0: beam waist; b: depth of focus; z_R: Rayleigh range; Θ: total angular spread

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Laser Beam Characteristics

- Laser beam intensity, I

$$I = I_0 e^{\frac{-2r^2}{w^2}}$$

  - Where I_o = Max. Intensity, r = Beam radius, ω = Beam waist radius

- Half angle of laser beam, θ

$$\theta = \frac{M^2 \lambda}{\pi w_0}$$

  - Where M^2 = Beam quality number (=1 for a perfect beam), λ= Wave length of beam.

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Laser Beam Characteristics

- Beam waist radius, ω_{02}

$$w_{02} = \frac{4M^2 \lambda f}{\pi D}.$$

  - Where f = Focal length of lens, D = 2 x Lens radius.

- Rayleigh range, Z_R (Z_R is the distance from the beam waist along the transverse plane where beam area has doubled)

$$z_R = \frac{\pi w_{02}^2}{\lambda}$$

Laser Material Interaction

- Energy absorbed by the beam, I

$$I = (1\text{-}R)\, I_0\, e^{(-\alpha z)}$$

- Where R = Reflectivity of the material,
- 1-R = Absorptivity of the material (A),
- I_0 = Incident intensity,
- α = Absorption coefficient,
- z = Depth of machining.

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Laser Material Interaction

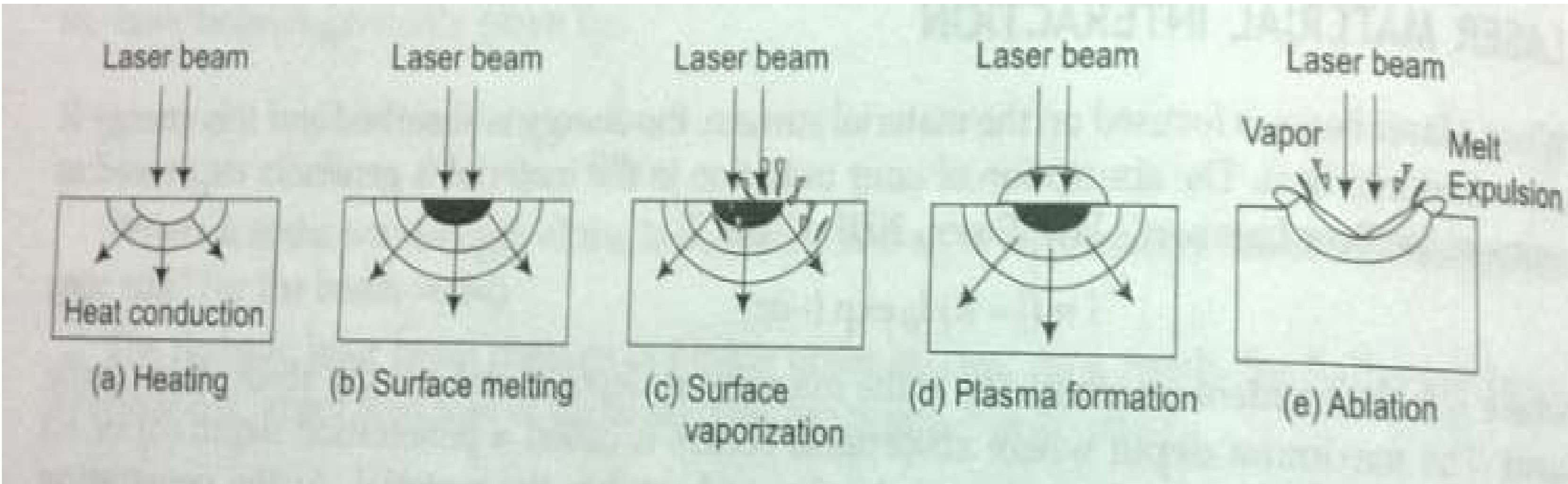

FIG. 2 Schematic of laser and material interaction.

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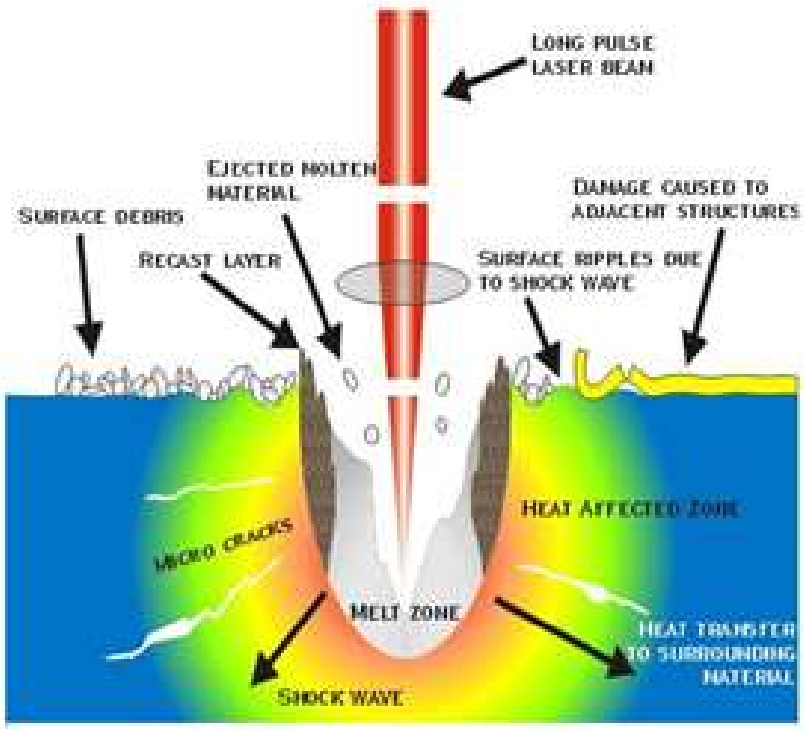
Process Parameters of LBM

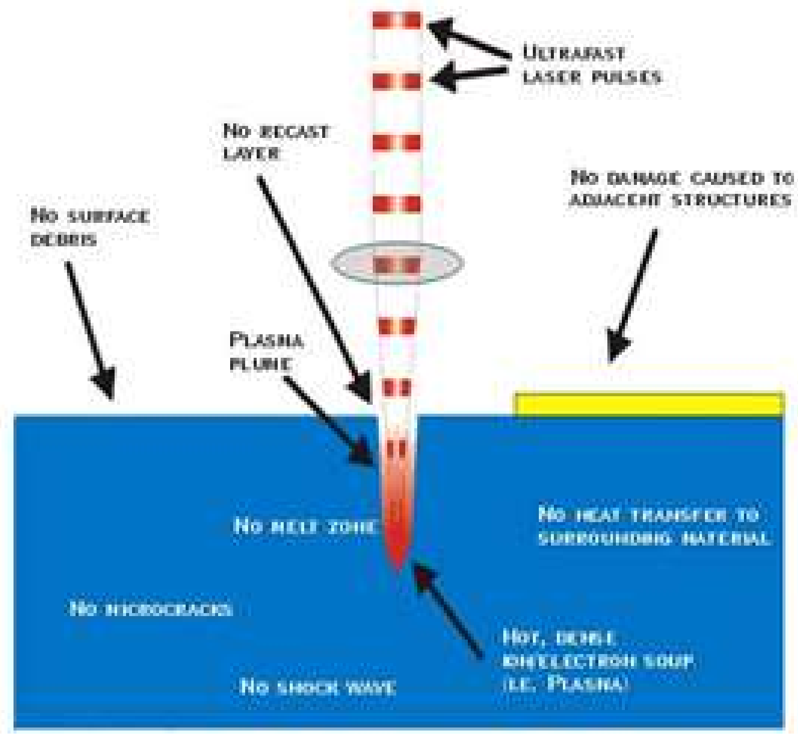
Process Parameters	Effect
1. Wave length / Focal length of lens	Feature size, Ablation rate
2. Beam shape (Gaussian/Square Wave)	Feature shape, Uniformity of the process
3. Beam energy, Pulse width	Size of HAZ
4. Pulse repetition range	Depth of material removal
5. Depth of focus	Aspect ratio
6. Vacuum / Inert gas environment	Size of recast layer

Long Vs Short Pulse Laser Machining

Long pulse



Short pulse



Short Pulse Laser Machining

1. Nanosecond Pulse Micromachining
2. Picosecond Pulse Micromachining
3. Femtosecond Pulse Micromachining

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1. Nanosecond Pulse Micromachining

Pulse duration: 1-10 ns (1 ns = 10^{-9} Sec.)

- Ablation depth, Za.

$$Za \approx \sqrt{Dt}\ \ln\left(\frac{F_a}{F_{th}}\right)$$

Where, D = Thermal diffusion coefficient,
t = Pulse duration,
Fa = Absorbed Fluence,
Fth = Threshold Fluence.

2. Picosecond Pulse Micromachining

Pulse duration: 1-10 ps (1 ps = 10^{-12} Sec.)

Ablation depth, Za.

$$Z_a \approx \alpha^{-1} \ln\left(\frac{F_a}{F_{th}}\right)$$

Where, α	=	Absorption depth,
Fa	=	Absorbed Fluence,
Fth	=	Threshold Fluence.

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3. Femtosecond Pulse Micromachining

Pulse duration: 1-10 fs (1 fs = 10^{-15} Sec.)

- In fs-laser ablation, no energy is transferred to the lattice but it is stored in a thin surface layer.
- Since the time for heat transfer is very less, metal evaporates instantaneously.
- Minimum HAZ & recast layer compared to ns & ps laser machining.

$$\text{Heat generated} = (D.t)^{1/2}$$

Where, D = Thermal diffusion coefficient,

t = Pulse duration

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Advantages & Disadvantages of LBM

- **Advantages**

1. No limit to cutting path as the laser point can move in any path.
2. The process is stress less, allowing very fragile materials to be laser cut without any support.
3. Very hard and abrasive material can be machined.
4. It is a cost effective and flexible process.
5. Non metals like plastic & rubber can be also machined.
6. No cutting lubricants required
7. No tool wear
8. Narrow heat affected zone

- **Disadvantages**

1. Skilled labour & expert CNC programmer is required
2. Limitations on thickness due to taper
3. High capital cost & maintenance cost
4. Safety precautions are required

Applications of LBM

1. Machining of small holes
2. Cutting complex profiles in thin & hard materials.
3. Partial cutting and engraving,
4. Sheet metal trimming,
5. Blanking
6. Precise aerospace applications,
7. Making cellular phone parts, Ink jet heads, medical devices…

THANK YOU...