

Non-Traditional Machining



ME 338: Manufacturing Processes II
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Singh/Melkote/Colton

Introduction

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



Nontraditional Machining

- Ultrasonic Machining (USM)
- Water-Jet Machining & Abrasive-Jet Machining
- Chemical Machining
- Electrochemical Machining (ECM)
- Electrical-Discharge Machining (EDM)
- High-Energy-Beam Machining
 - Laser-beam machining (LBM)
 - Electron-beam machining (EBM)

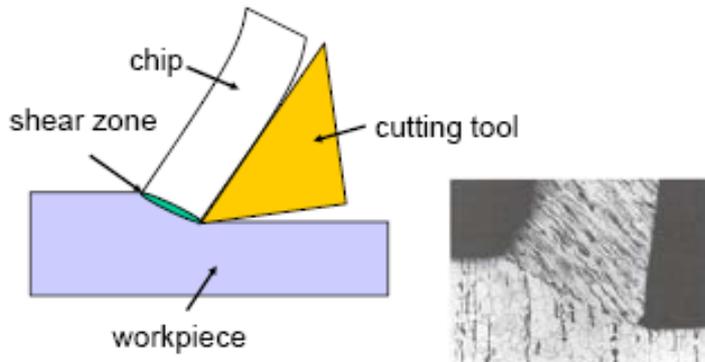


Traditional vs. Nontraditional

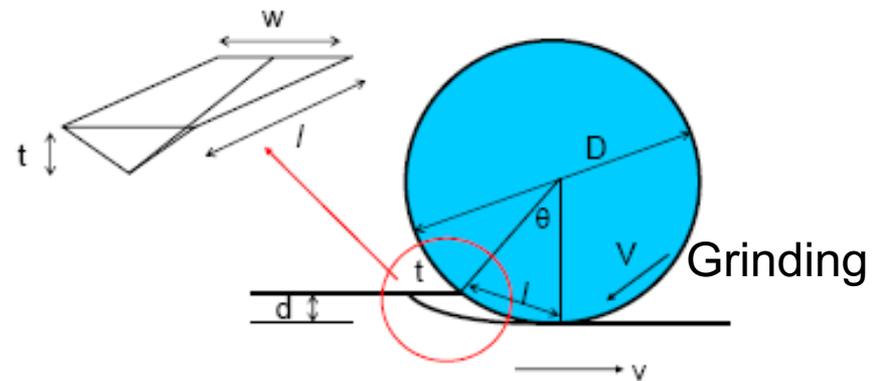
- Primary source of energy
 - Traditional: mechanical.
 - Nontraditional: electrical, chemical, optical
- Primary method of material removal
 - Traditional: shearing
 - Nontraditional: does not use shearing (e.g., abrasive water jet cutting uses erosion)



Water jet machining



2D cutting process



Grinding



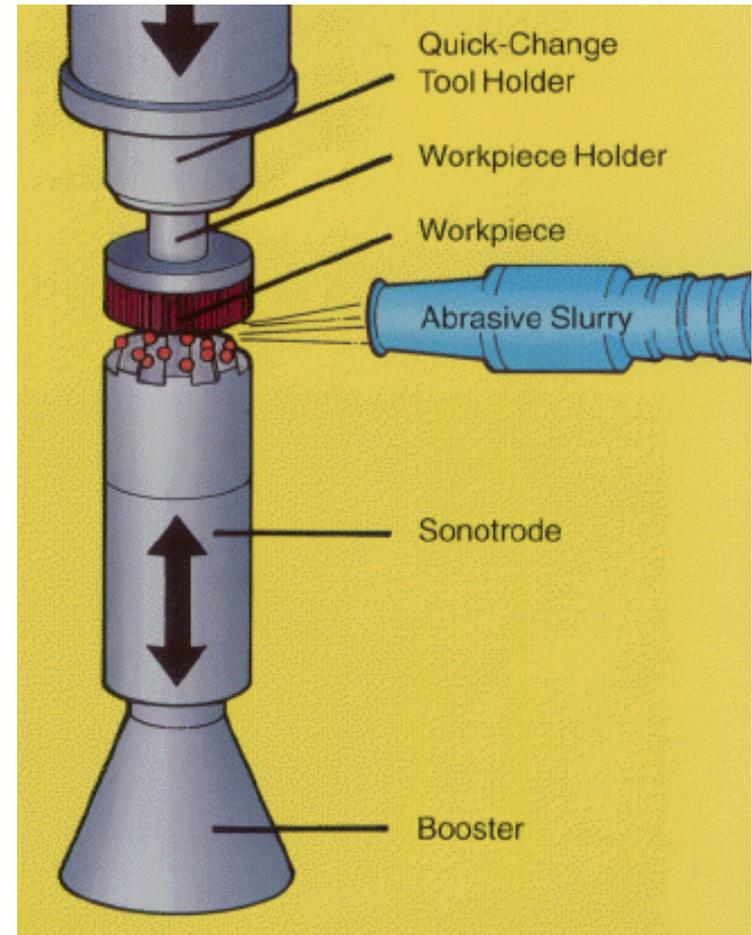
Why Nontraditional Machining?

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



Ultrasonic Machining (USM)

- Process description
 - The tool, which is negative of the workpiece, is vibrated at low amplitude (0.013 to 0.08 mm) and high frequency (about 20 kHz) in an abrasive grit slurry at the workpiece surface.
 - The slurry also carries away the debris from the cutting area.
 - The tool is gradually moved down maintaining a constant gap of approximately 0.1 mm between the tool and workpiece surface.



USM (Cont.)

- Cracks are generated due to the high stresses produced by particles striking a surface.
- The time of contact between the particle and the surface is given by:

$$t_0 \approx \frac{5r}{c_0} \left(\frac{c_0}{v} \right)^{1/5} \quad (10 - 100 \mu s)$$

r : radius of a spherical particle

c_0 : workpiece elastic wave velocity = $\sqrt{E / \rho}$

v : velocity of particle striking surface

Force of a particle on surface:

$$F = d(mv) / dt$$

Average force of a particle striking the surface:

$$F_{ave} = 2mv / t_0$$



USM (Cont.)

- *Example:* Explain what change, if any, takes place in the magnitude of the impact force of a particle in ultrasonic machining as the temperature of the workpiece is increased.

Solution:

Here, m and v are constant.

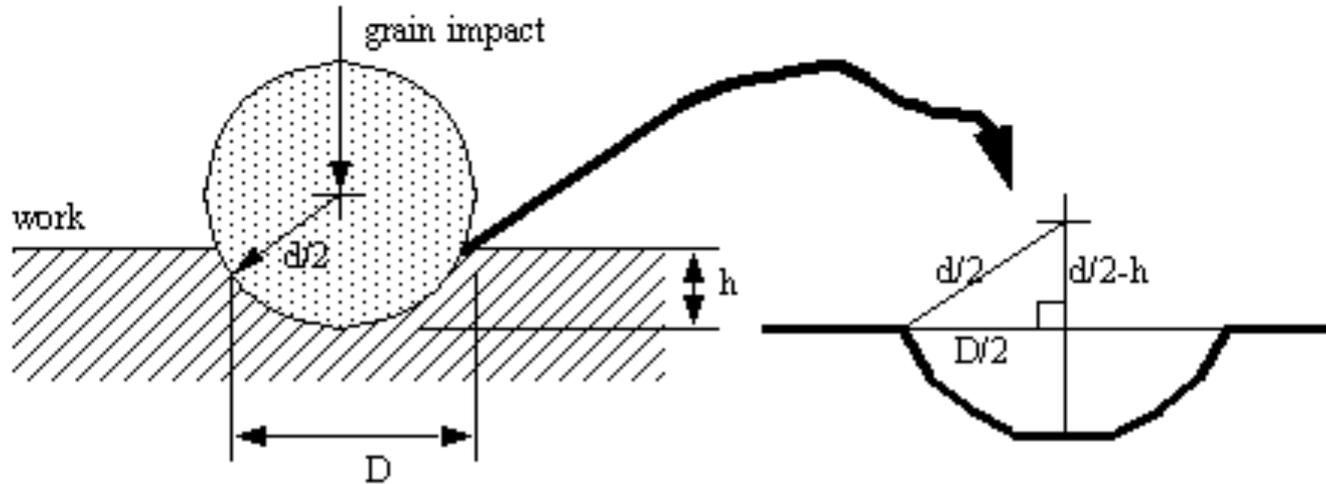
$$t_0 = \frac{5r}{c_0} \left(\frac{c_0}{v} \right)^{1/5} \Rightarrow t_0 \propto \frac{1}{c_0^{4/5}} \propto \frac{1}{E^{2/5}}$$

When temperature increases, E decreases and t_0 increases. Hence, F decreases.



USM (Cont.)

Assuming hemispherical brittle fracture



$$V = \frac{2\pi}{3} \left(\frac{D}{2} \right)^3$$

$$D \approx 2\sqrt{dh}$$

$$V = \frac{2\pi}{3} (dh)^{3/2}$$

$$\text{MRR} = \eta V Z f$$

where V = volume removed by a single grain

f = frequency of operation

Z = number of particles impacting per cycle

η = efficiency

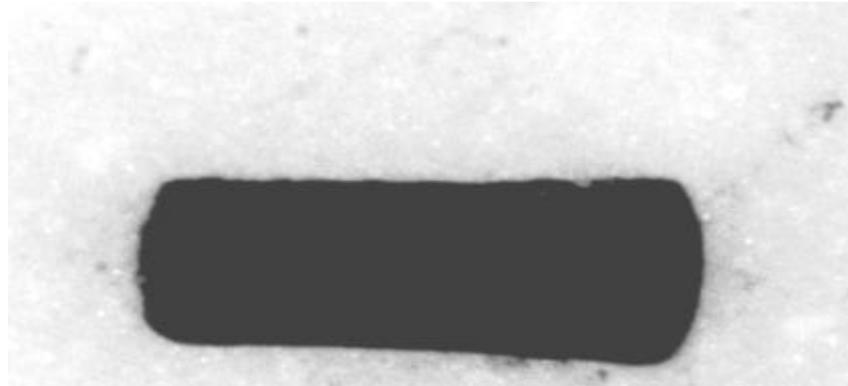


USM (Cont.)

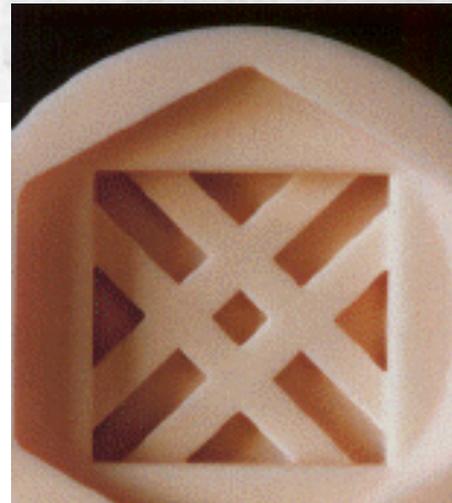
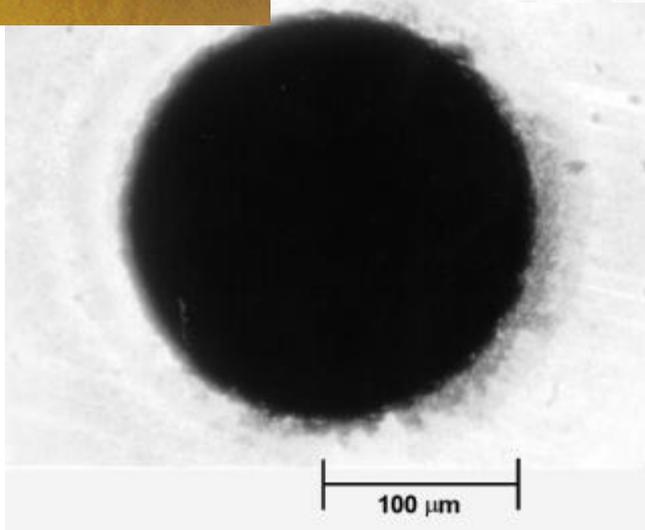
- Applications
 - USM is best suited for hard, brittle materials, such as ceramics, carbides, glass, precious stones, and hardened steels. (Why?)
- Capability
 - With fine abrasives, tolerance of 0.0125 mm or better can be held. R_a varies between 0.2 – 1.6 μm .
- Pros & Cons:
 - *Pros*: precise machining of brittle materials; makes tiny holes (0.3 mm); does not produce electric, thermal, chemical damage because it removes material mechanically.
 - *Cons*: low material removal rate (typically 0.8 cm^3/min); tool wears rapidly; machining area and depth are limited.



USM Parts

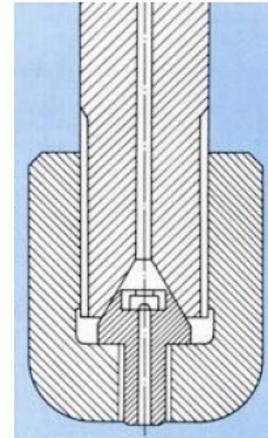
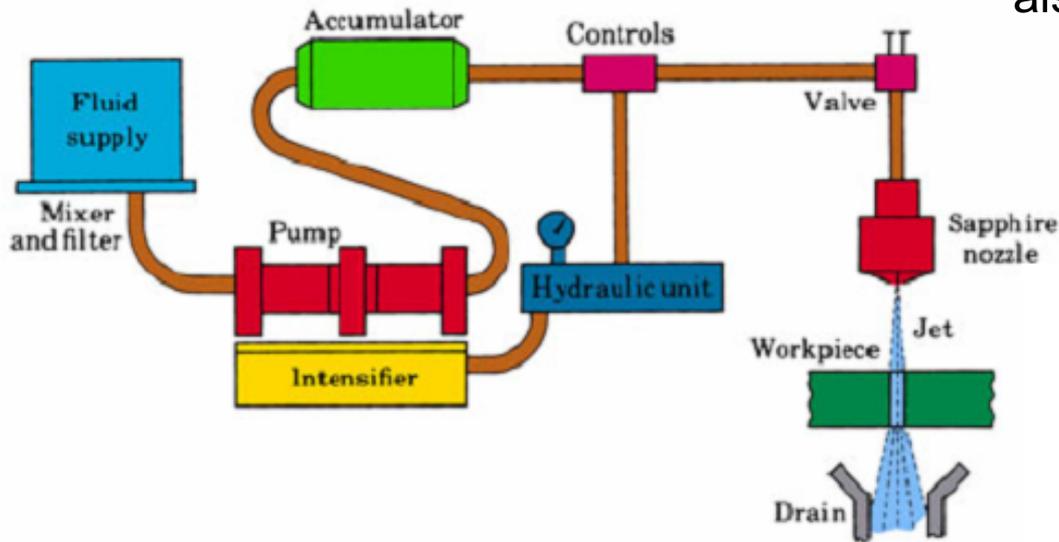


Ceramic



Water-Jet Machining (WJM)

also called hydrodynamic machining



nozzle

WJM is a form of micro erosion. It works by forcing a large volume of water through a small orifice in the nozzle.

The extreme pressure of the accelerated water particles contacts a small area of the workpiece and acts like a saw and cuts a narrow groove in the material.

<http://www.flowcorp.com/waterjet-resources.cfm?id=360>



WJM (Cont.)

- Pros: no need for predrilled holes, no heat, no workpiece deflection (hence suitable for flexible materials), minimal burr, environmentally friendly.
- Cons: limited to material with naturally occurring small cracks or softer material.
- Applications:
 - Mostly used to cut lower strength materials such as wood, plastics, rubber, paper, leather, composite, etc.
 - Food preparation
 - Good for materials that cannot withstand high temperatures of other methods for stress distortion or metallurgical reasons.



WJM Examples



cake



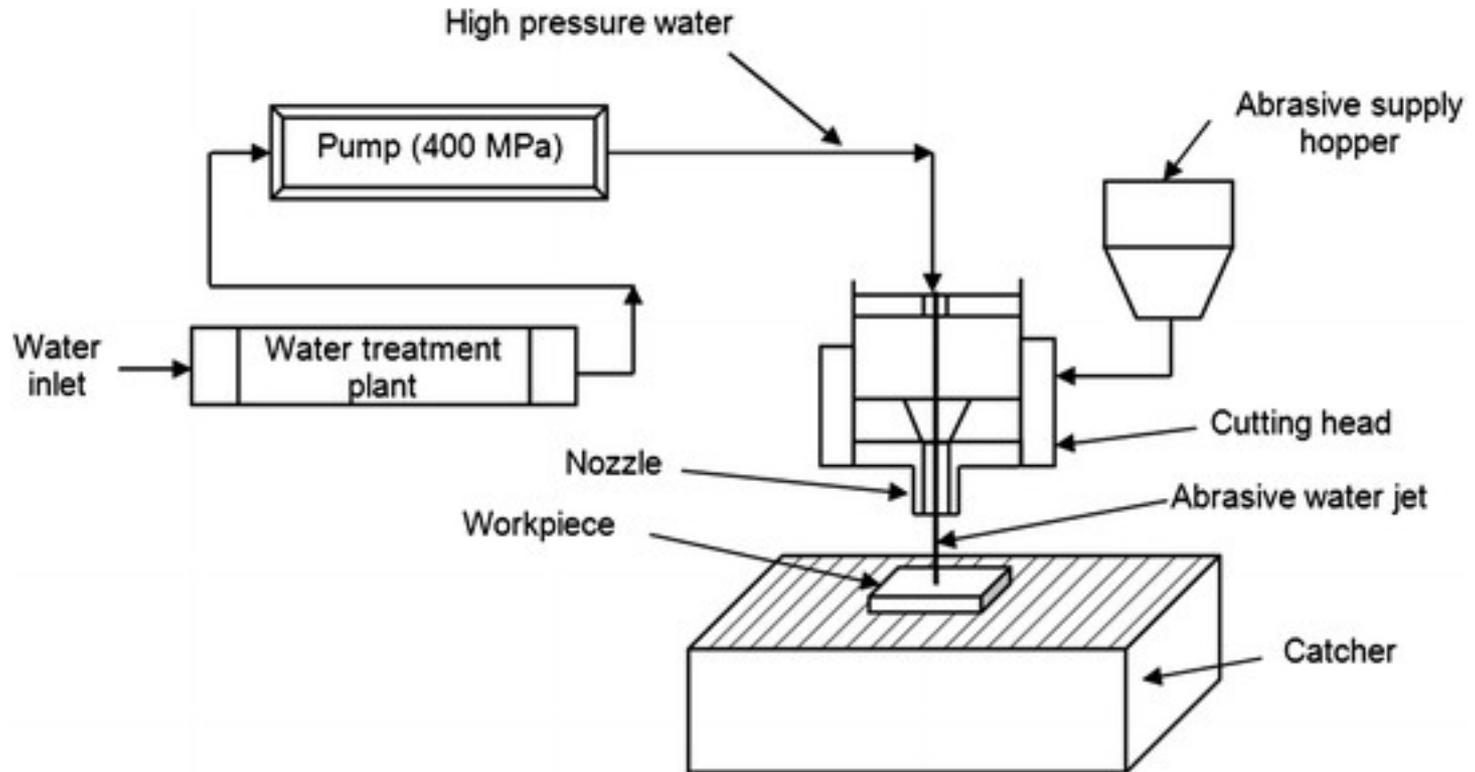
fish



PWB (printed wire board)



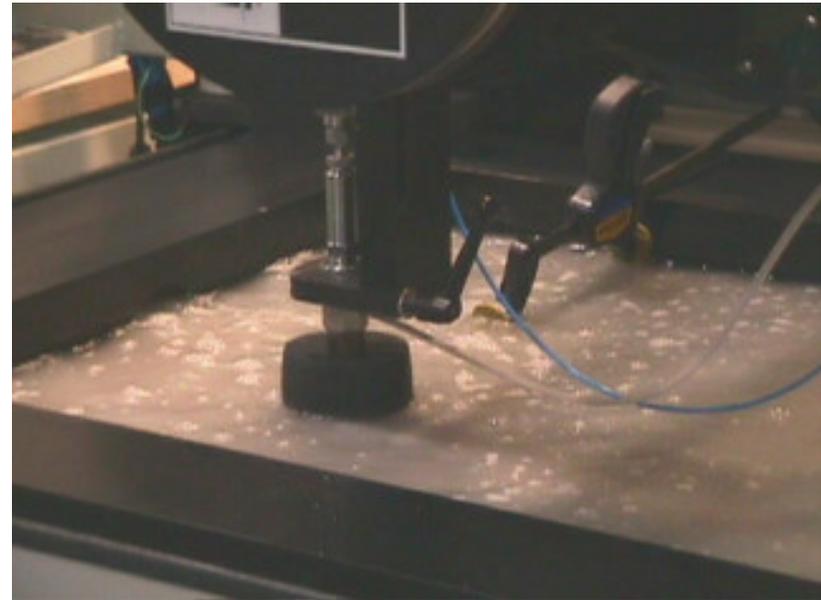
AWJM



Abrasive Water-Jet Machining (AWJM)

The water jet contains abrasive particles such as silicon carbide, thus increasing MRR.

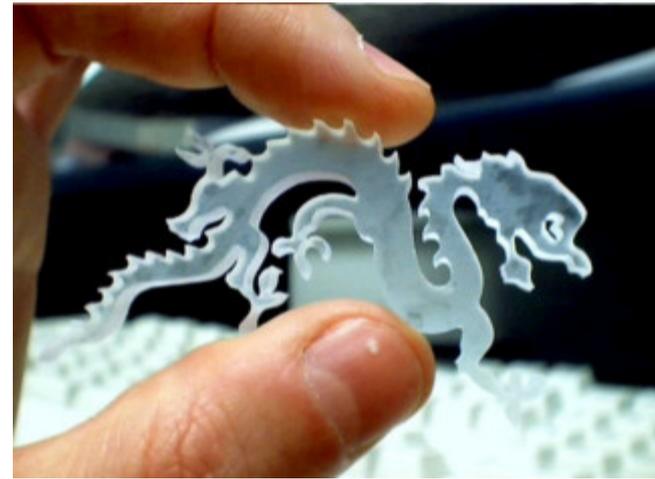
Metallic materials can be cut. Particularly suitable for heat-sensitive materials.



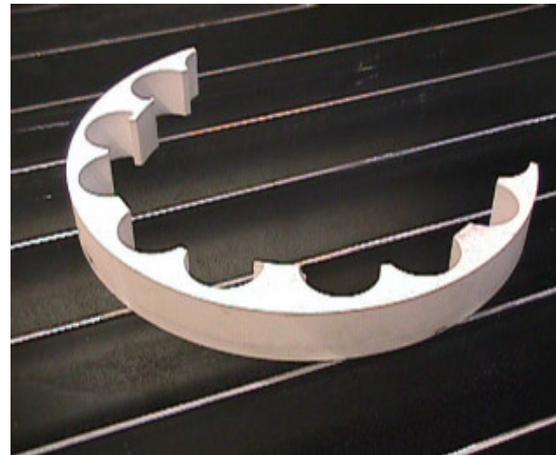
AWJM Parts



Steel rack (75 mm thick)



Bullet Proof Glass Part

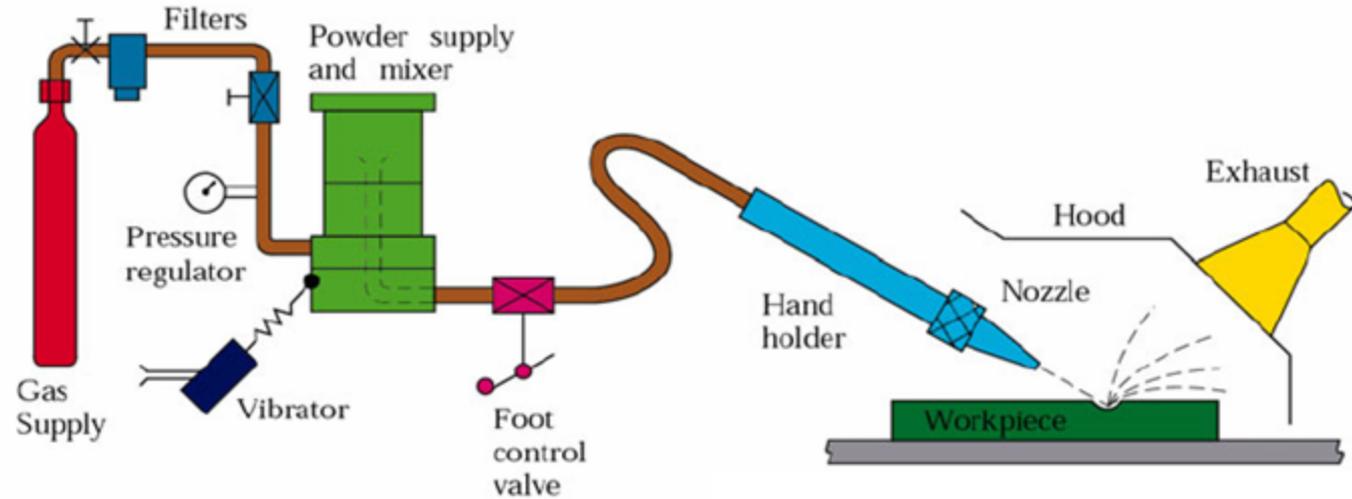


Ceramic Part

Source: <http://www.waterjets.org/>



Abrasive-Jet Machining (AJM)



A high-velocity jet of dry air, nitrogen, or carbon dioxide containing abrasive particles is aimed at the workpiece surface under controlled conditions.

The gas supply pressure is on the order of 850 kPa (125 psi) and the jet velocity can be as high as 300 m/s and is controlled by a valve.



AJM Process Capability

- Material removal
 - Typical cutting speeds vary between 25 -125 mm/min
- Dimensional Tolerances
 - Typical range $\pm 2 - \pm 5 \mu\text{m}$
- Surface Finish
 - Typical R_a values vary from 0.3 - 2.3 μm



AJM Applications & Limitations

- Applications
 - Can cut traditionally hard to cut materials, e.g., composites, ceramics, glass
 - Good for materials that cannot stand high temperatures
- Limitations
 - Expensive process
 - Flaring can become large
 - Not suitable for mass production because of high maintenance requirements



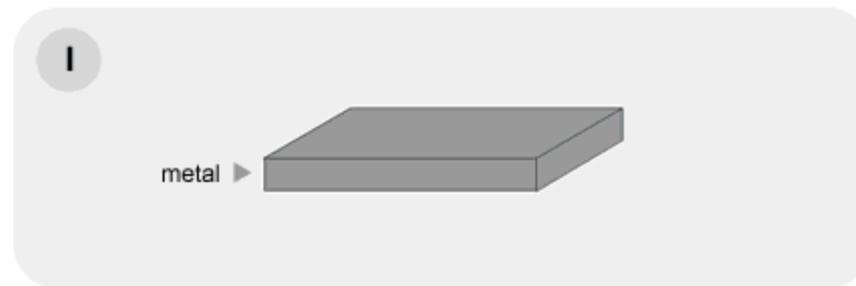
Chemical Machining (CM)

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



CM (Cont.)

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



Chemically cleaned surface



CM (Cont.)

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



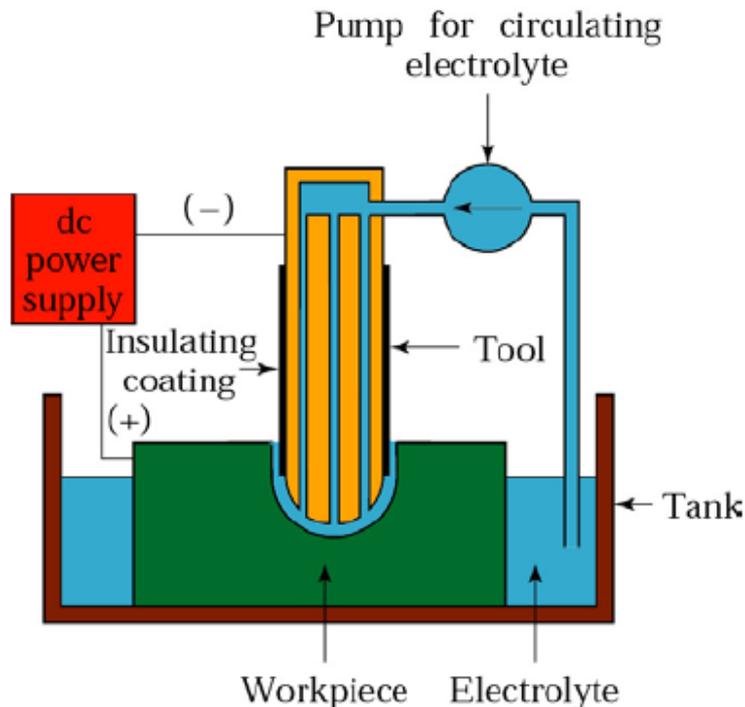
Pros: low setup, maintenance, and tooling costs; small, delicate parts can be machined; suitable for low production runs on intricate designs.

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



Electrochemical Machining (ECM)

- Process description:



- In ECM, a dc voltage (10-25 v) is applied across the gap between a pre-shaped cathode tool and an anode workpiece. The workpiece is dissolved by an electrochemical reaction to the shape of the tool.
- The electrolyte flows at high speed (10-60 m/s) through the gap (0.1-0.6 mm) to dissipate heat and wash away the dissolved metal.



ECM (Cont.)

- The material removal rate by ECM is given by:

$$MRR = C I \eta$$

where, $MRR = \text{mm}^3/\text{min}$, $I = \text{current in amperes}$,

$\eta = \text{current efficiency}$, which typically ranges from 90-100%,

C is a material constant in $\text{mm}^3/\text{A}\cdot\text{min}$.

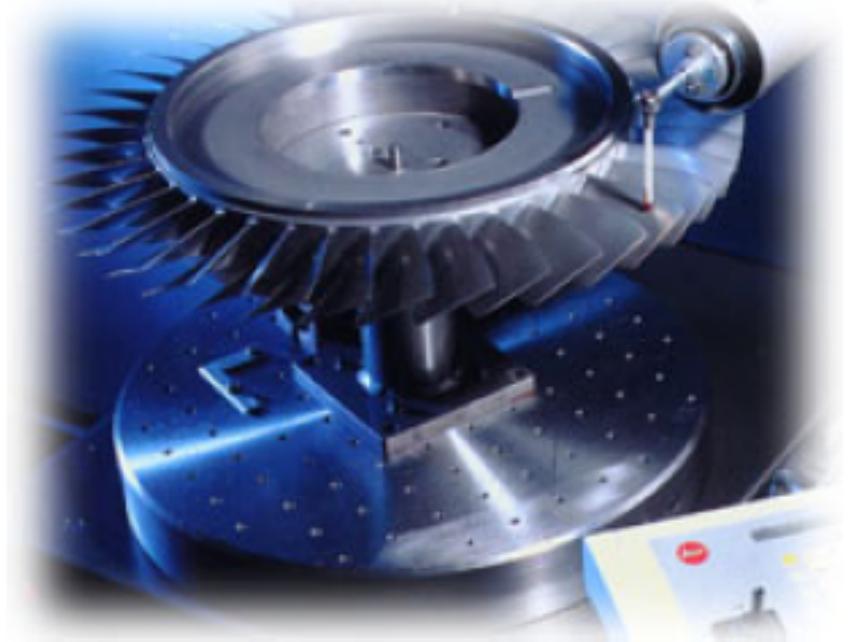
Feed rate (mm/min): $f = MRR / A_0$

Assuming a cavity with uniform cross-sectional area A_0



ECM (Cont.)

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



EDM-History

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



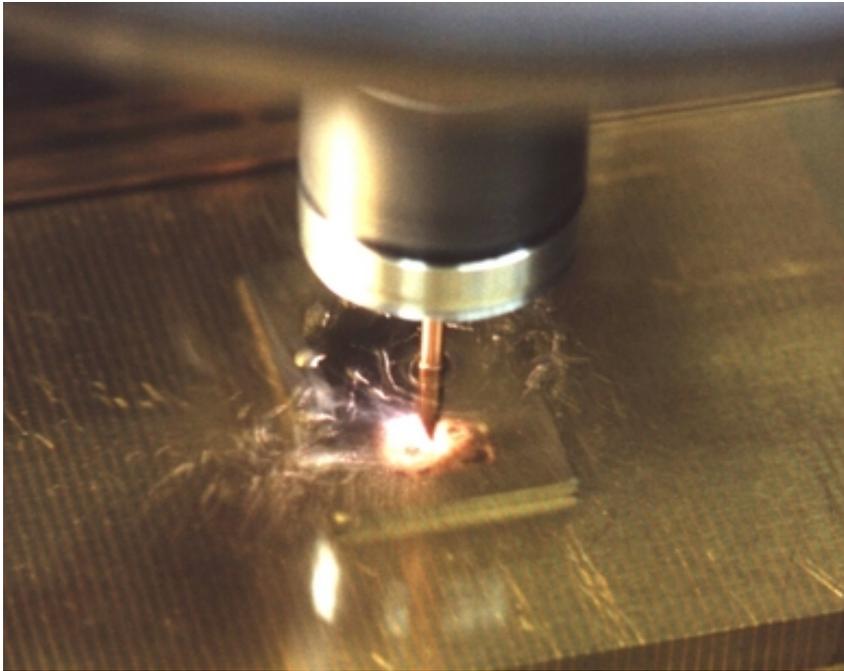
Mr. & Mrs. Lazarenko at the presentation of the Eleroda D1 at the EMO exhibition in Milan Italy.

First industrial EDM machine in the world.

Mrs. Lazarenko



Electrical Discharge Machining (EDM)



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

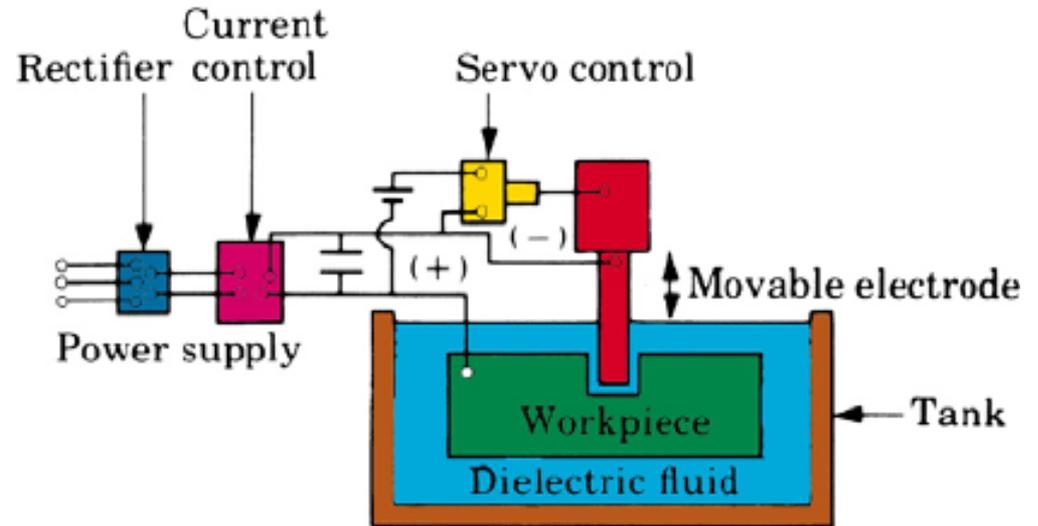
EDM is one of the most accurate while quite affordable mfg process.



EDM (Cont.)

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

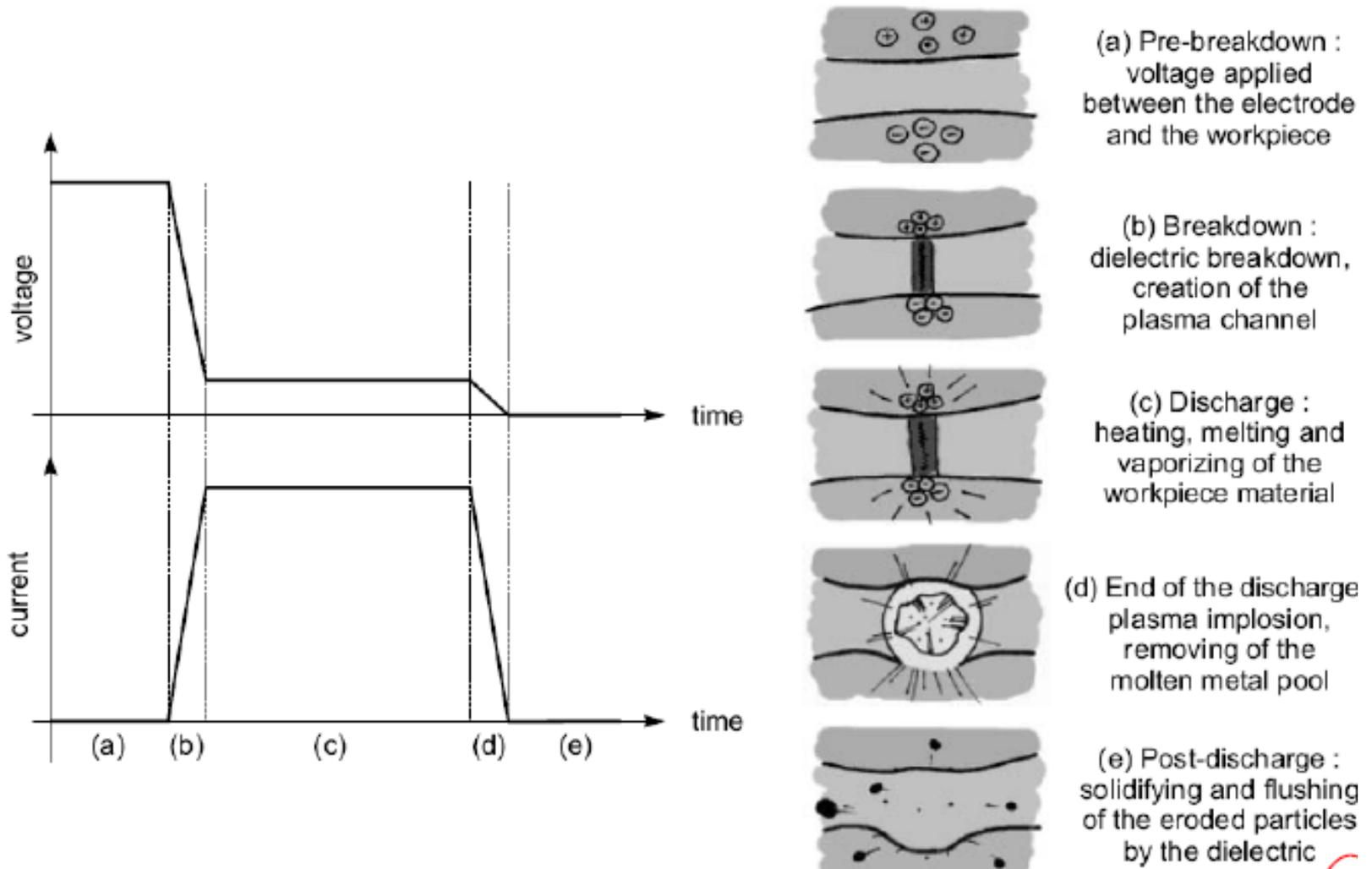
When the potential difference is sufficiently high, a transient spark discharges through the fluid, removing a very small amount of metal from the workpiece.



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



Process-Basics



EDM (Cont.)

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

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

An approximate empirical relationship is:

$$MRR = 4 \times 10^4 I T_w^{-1.23}$$

MRR=mm³/min

I=current in amperes

T_w =melting point of workpiece (°C)

Wear rate of electrode:

$$W_t = 11 \times 10^3 I T_t^{-2.38}$$

W_t =mm³/min

T_t =melting point of electrode material (°C)

Wear ratio of workpiece to electrode:

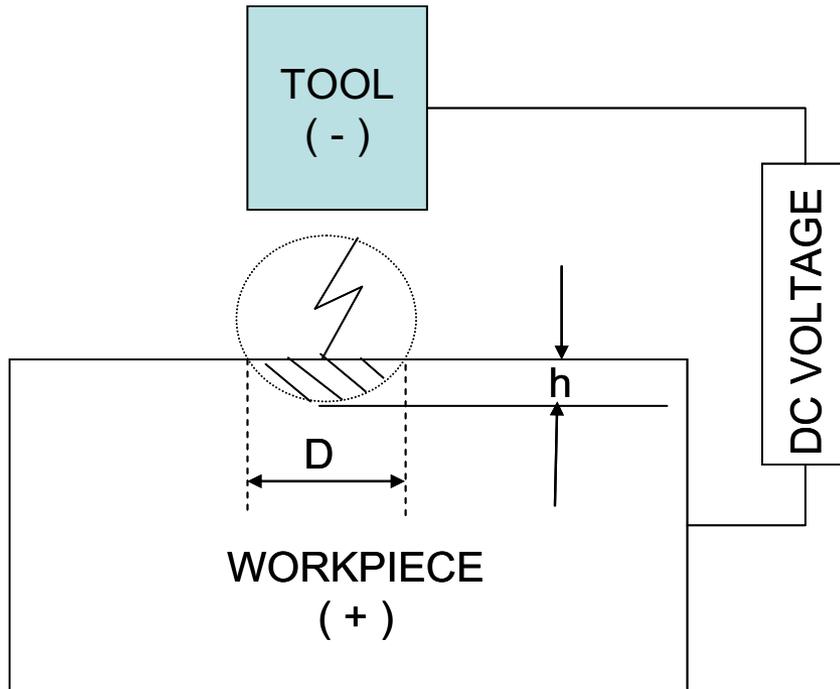
$$R = 2.25 T_r^{-2.3}$$

T_r =ratio of workpiece to electrode melting points (°C)



MRR - EDM

- Experimental Approach



Scheme of Crater Formation

$$MRR = V_c f \eta$$

where f = frequency of operation and η = efficiency

Metal removal is function of pulse energy and frequency:

$$h = K_1 W^n$$

$$D = K_2 W^n$$

where W = Pulse energy, J

h = height of crater, mm

D = diameter of crater, mm

K_1, K_2 = constants depending on electrode materials and dielectric

n = constant depending on work tool combination

The crater volume from geometry,

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

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

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



Volume of the crater

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

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

$$\text{In[17]:- } \int_0^h \pi (2 r h - h^2) dh$$

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

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

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

$$\text{Out[19]:- } \frac{1}{24} h (3 D^2 + 4 h^2) \pi$$



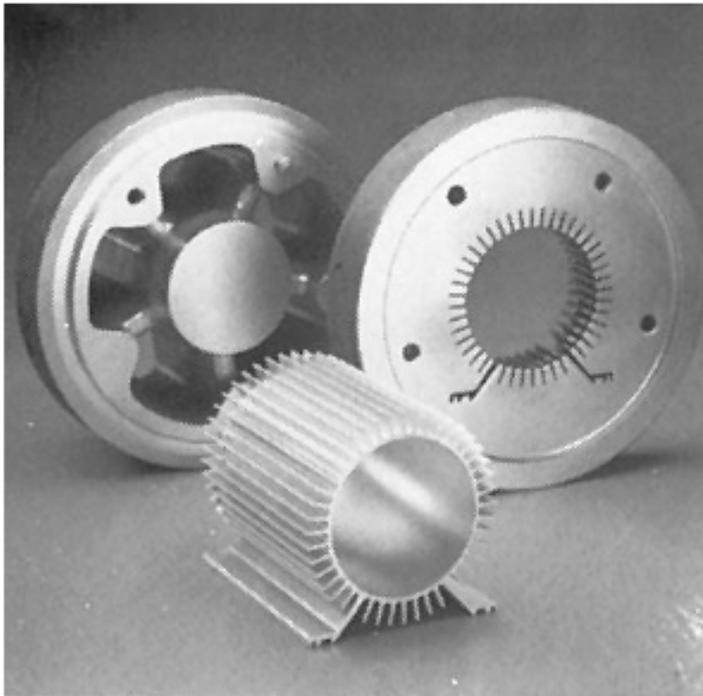
EDM Process Capability

- MRR
 - Range from 2 to 400 mm³/min. High rates produce rough finish, having a molten and recast structure with poor surface integrity and low fatigue properties.
- Dimensional Tolerances
 - Function of the material being processed
 - Typically between ± 0.005 - ± 0.125 mm
- Surface Finish
 - Depends on current density and material being machined
 - R_a varies from 0.05 – 12.5 μm
 - New techniques use an oscillating electrode, providing very fine surface finishes.

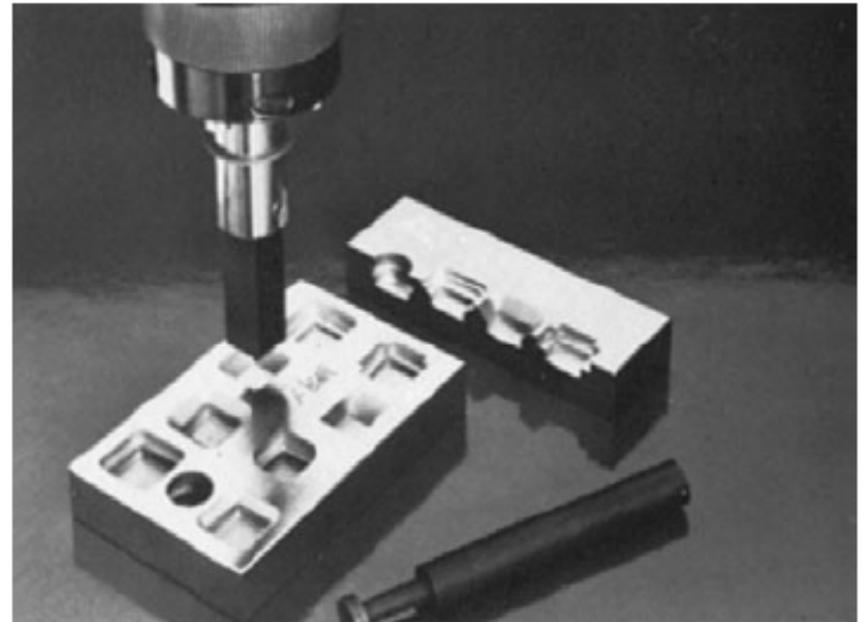


EDM Applications

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



Cavities produced by EDM



Stepped cavities

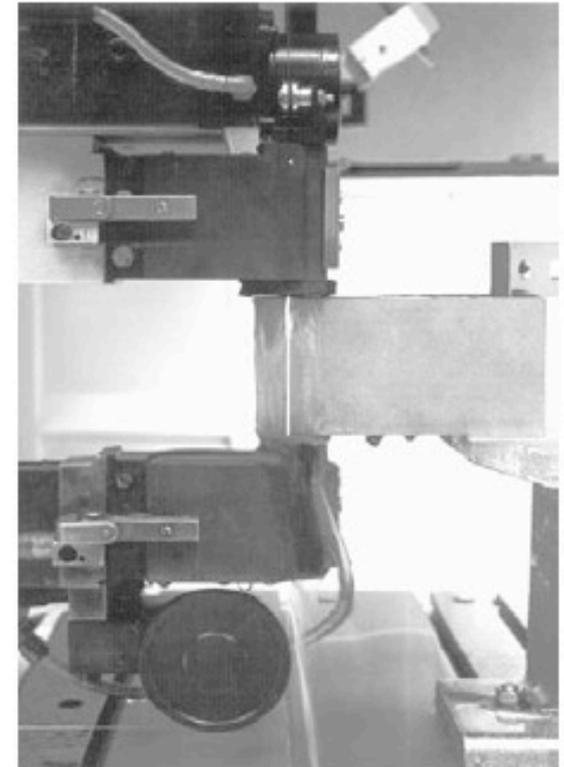
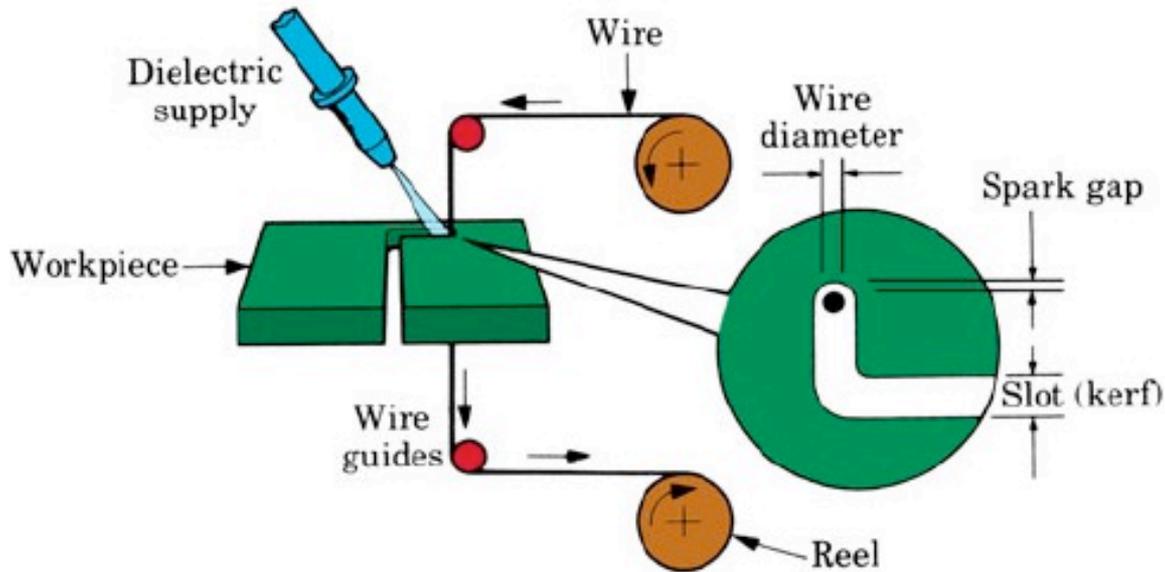


EDM Limitations

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



Wire EDM



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



Wire EDM (Cont.)

MRR in Wire EDM

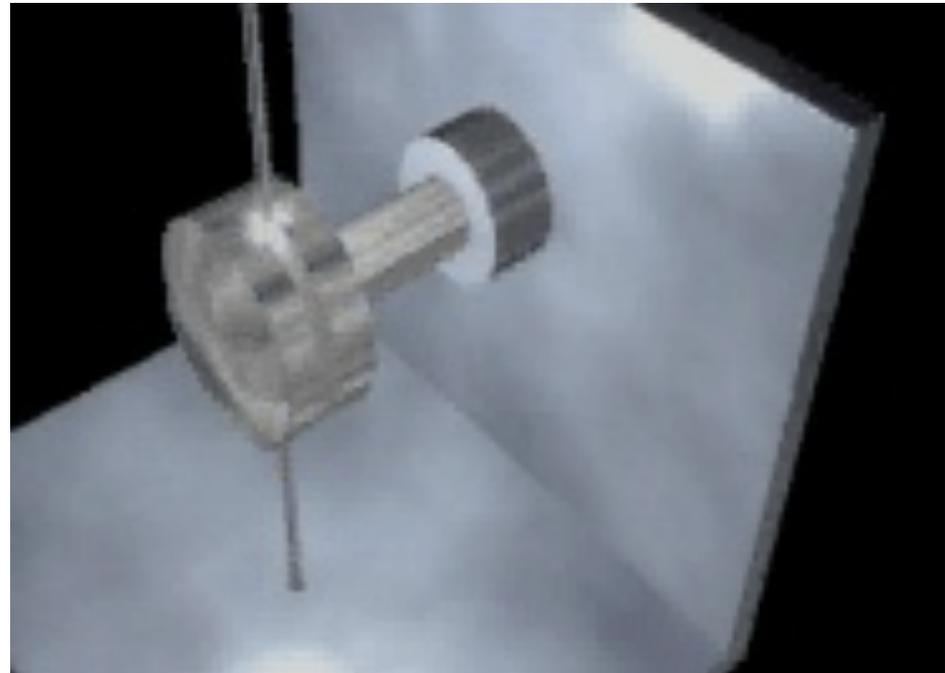
$$MRR = V_f h b$$

where, $b = d_w + 2s$

$$MRR = \text{mm}^3/\text{min}$$

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

h = workpiece thickness or height in mm

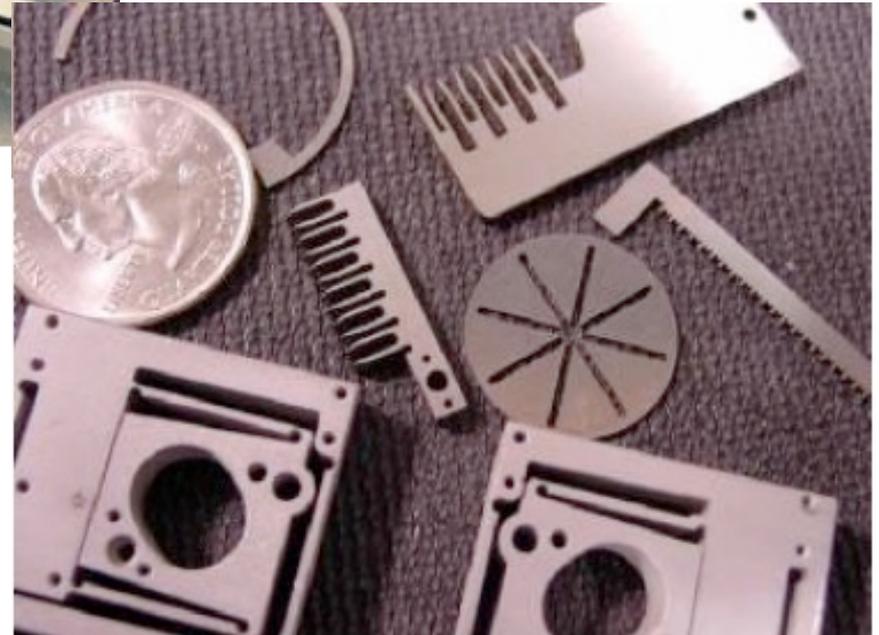


d_w = wire diameter in mm

s = gap between wire and workpiece in mm



Wire EDM Parts

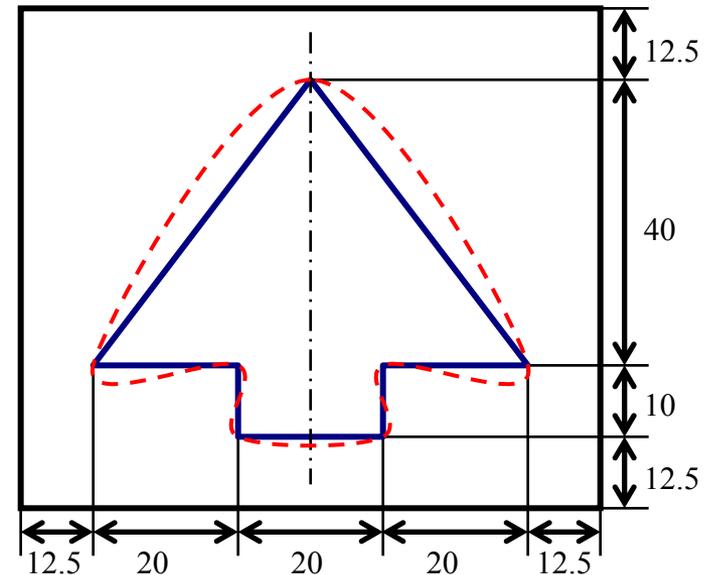


Example

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

Assumptions:

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



Example

Solution:

- EDM process

$$V_{EDM} = l_c \cdot (dw + 2s) \cdot t = 1440 \text{ mm}^3$$

- Conventional machining

$$V_M = V_{total} - V_{part} = 99500 \text{ mm}^3$$

- Power comparison

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

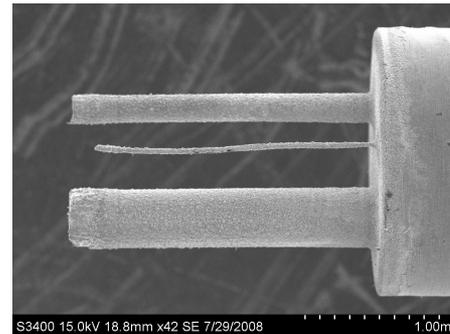
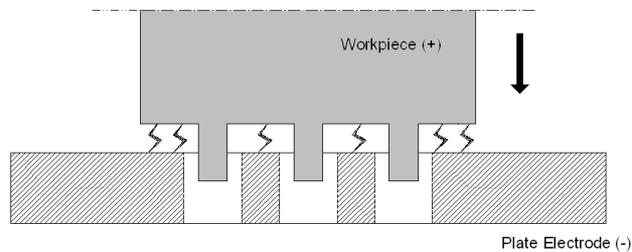
let's assume $t_{EDM} = \alpha t_M$

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



Reverse micro-EDM

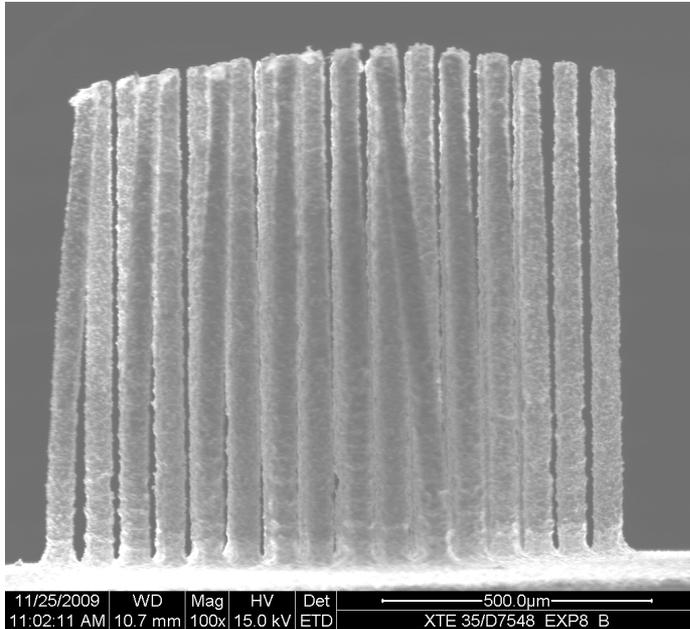
- Fabrication of high aspect ratio micro-electrode arrays



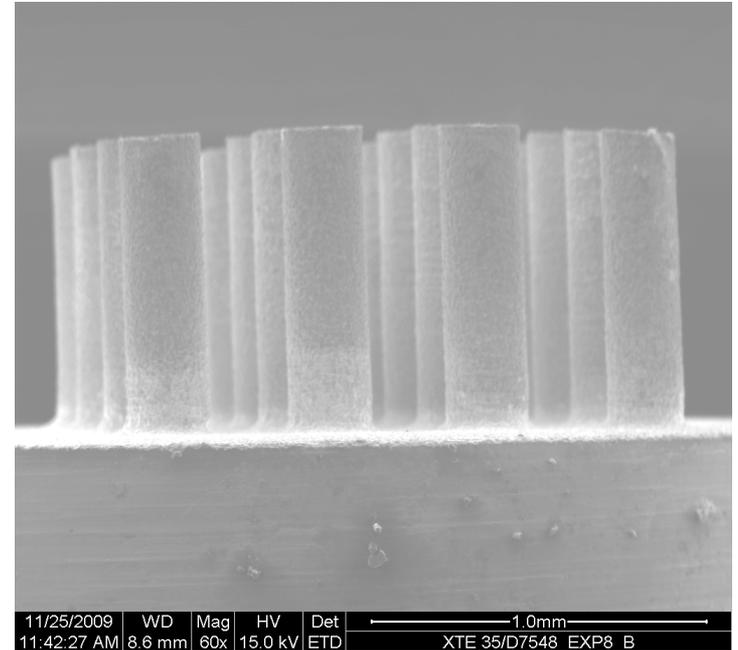
- Potential application in machining hole arrays via micro-EDM/ECM



Arrays Fabricated via R μ -EDM @IITB



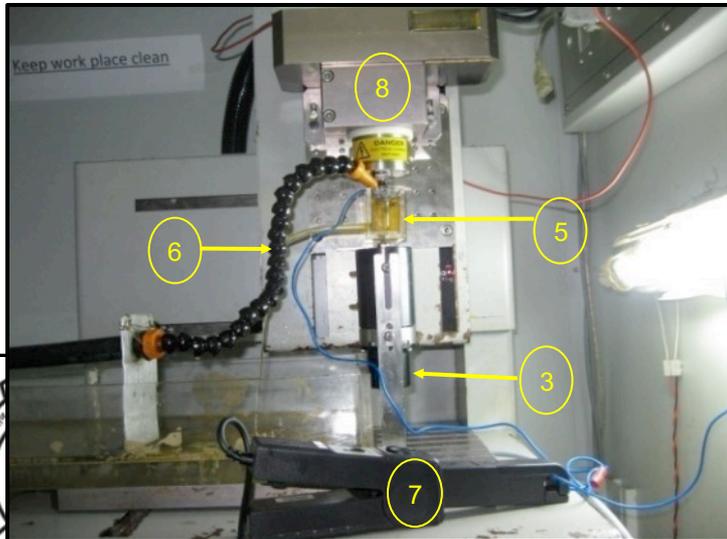
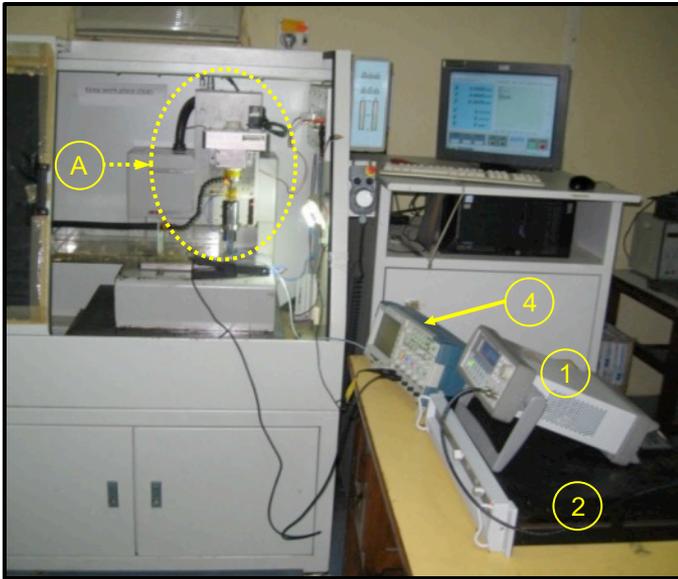
6x6 array



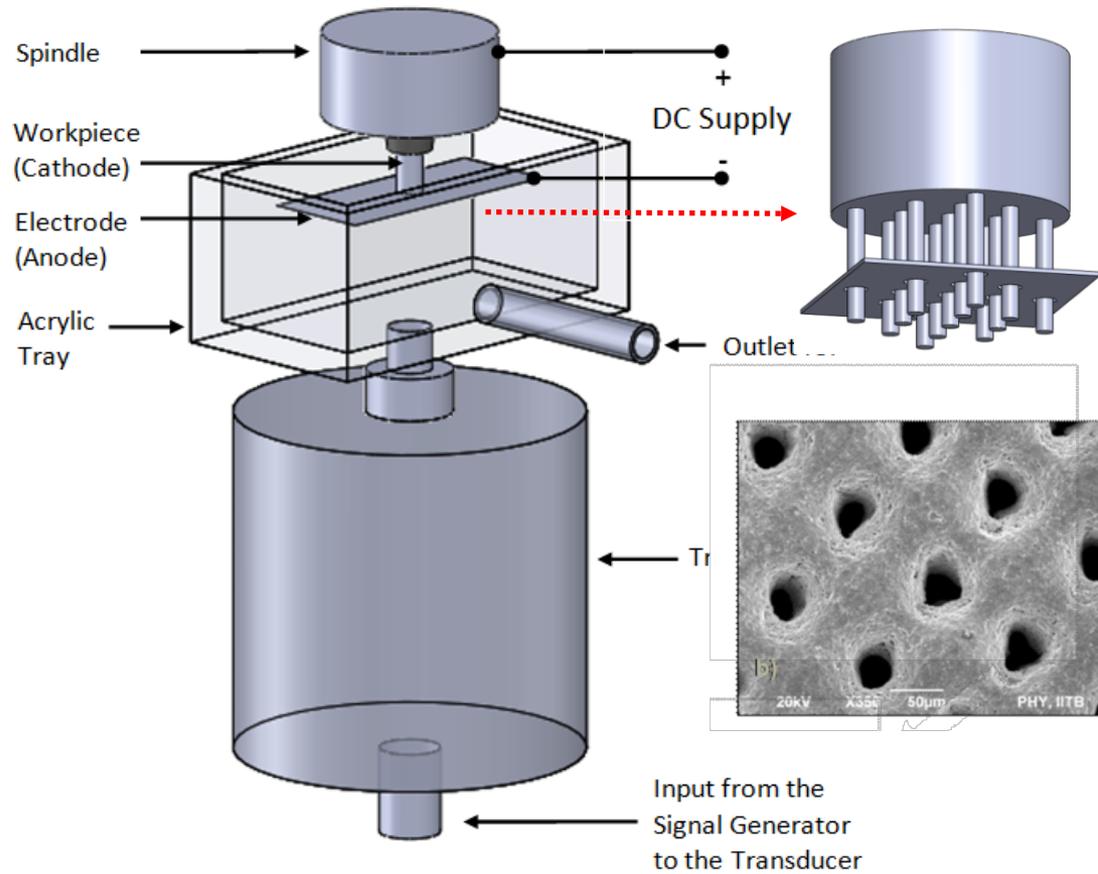
4x4 array



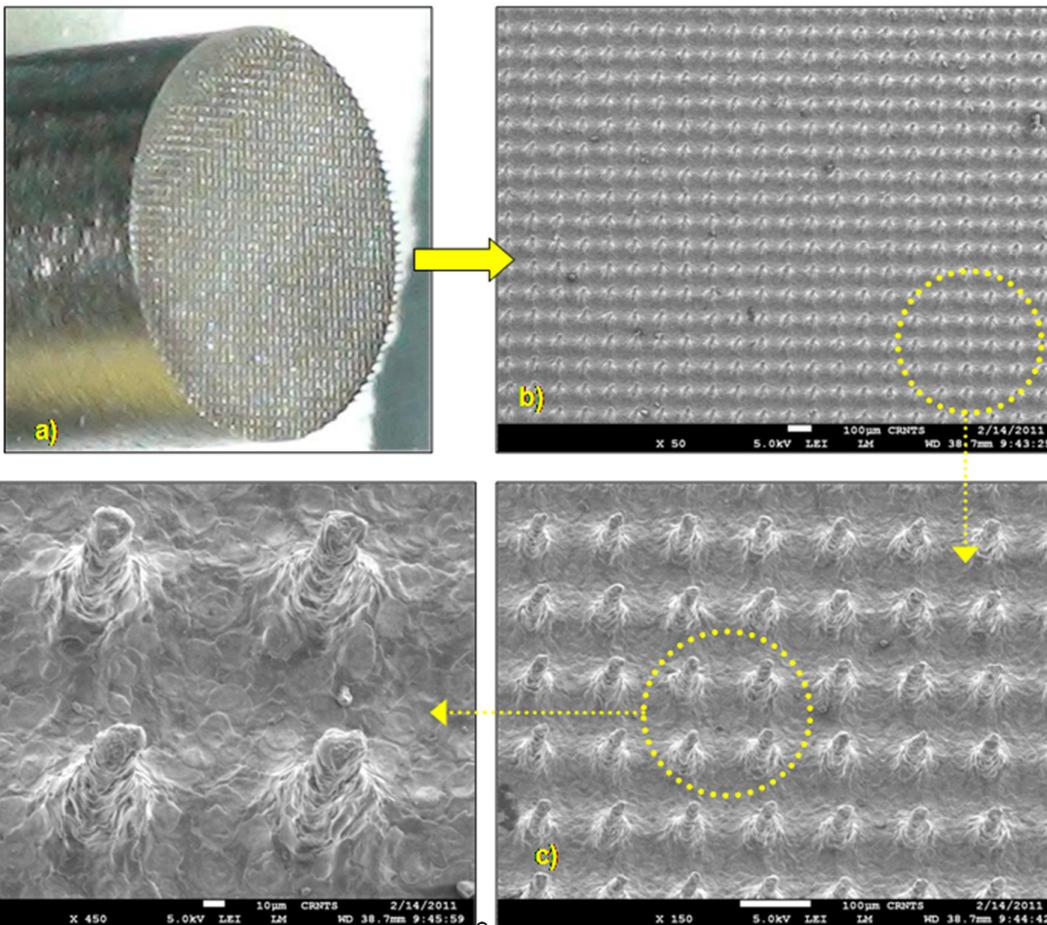
Experimental Setup



Enlarged view of A



Fabricated Texture



ME 338: Manufacturing Processes II

High-Energy-Beam Machining

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

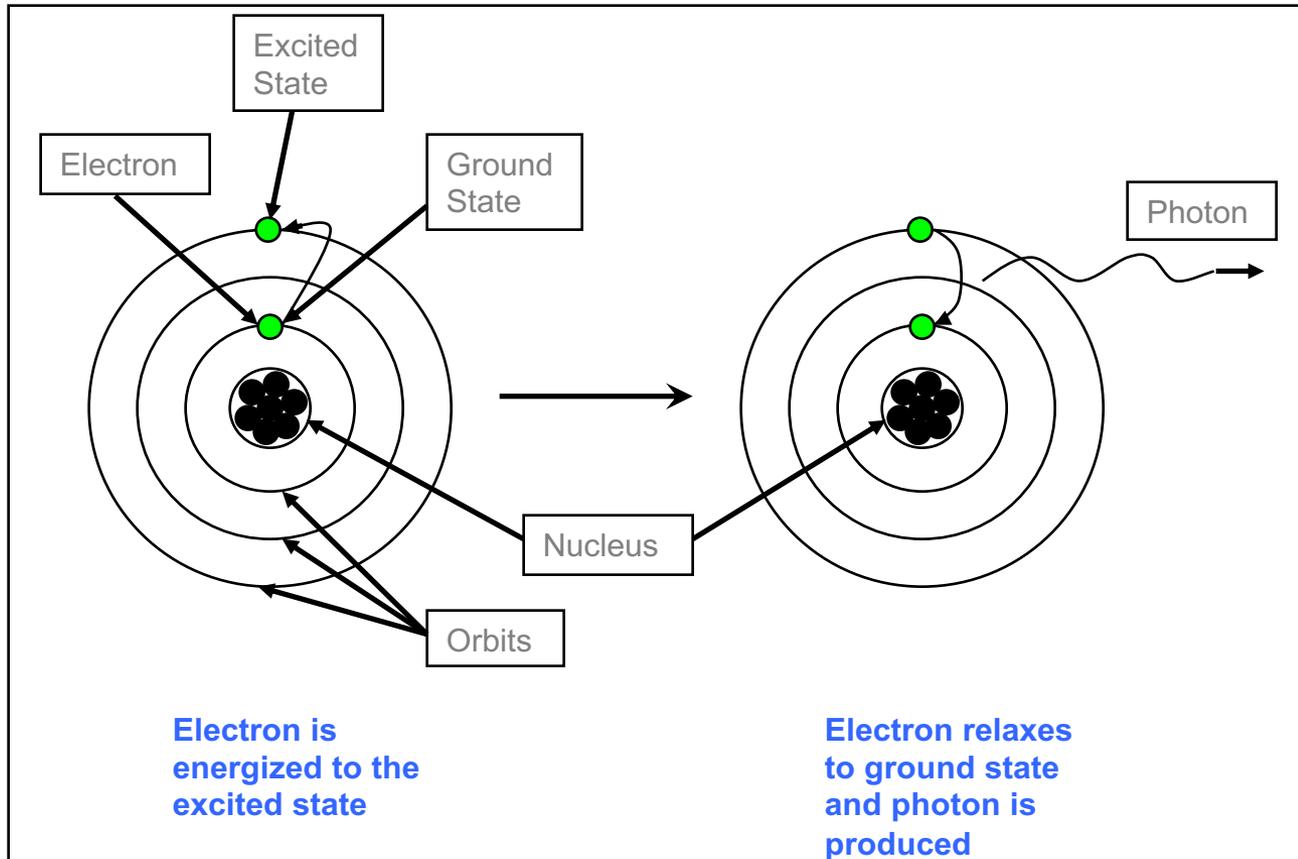


Laser-Beam Machining (LBM)

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



LBM (Cont.)

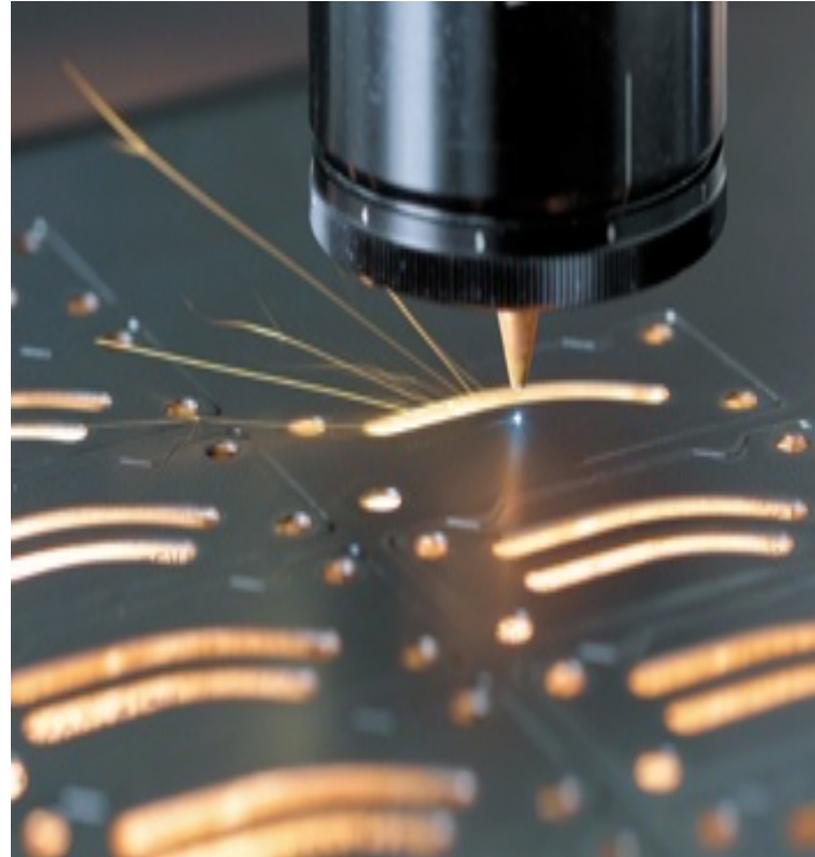


Photon Emission Model

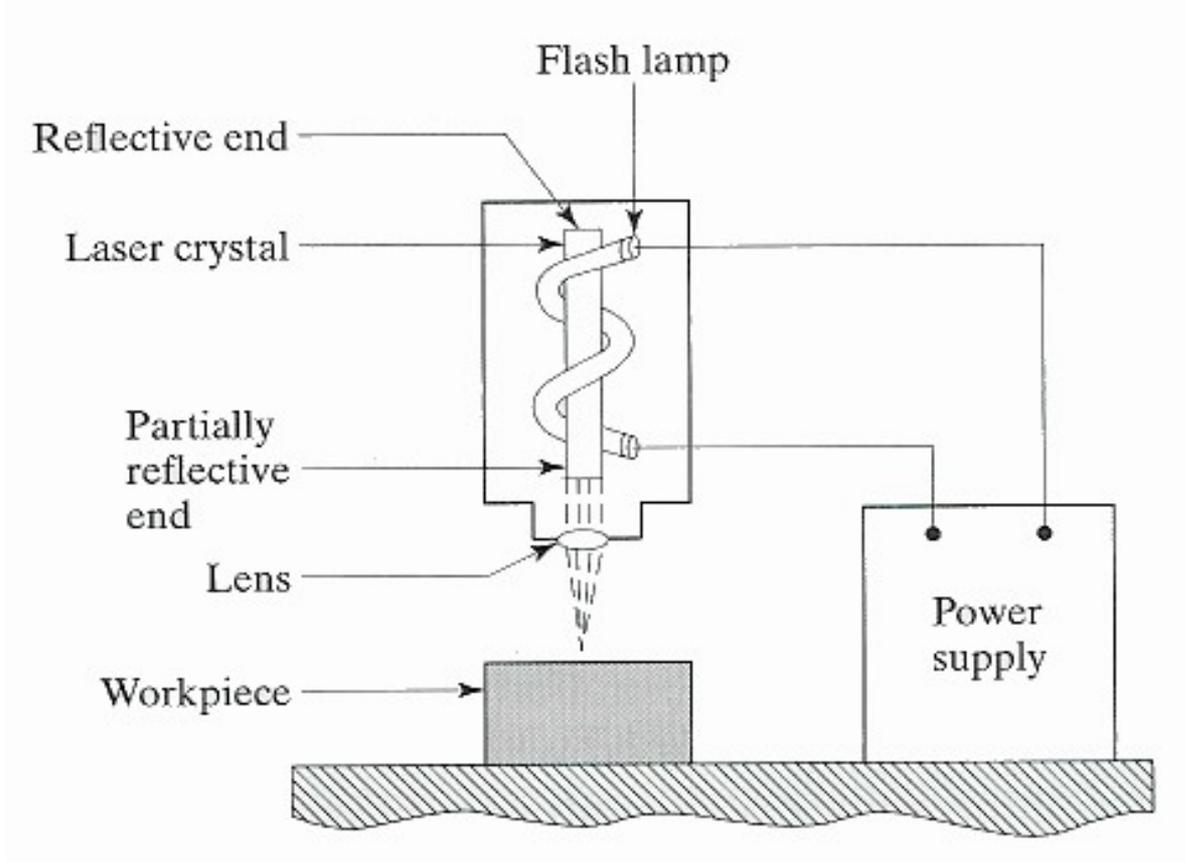


LBM (Cont.)

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



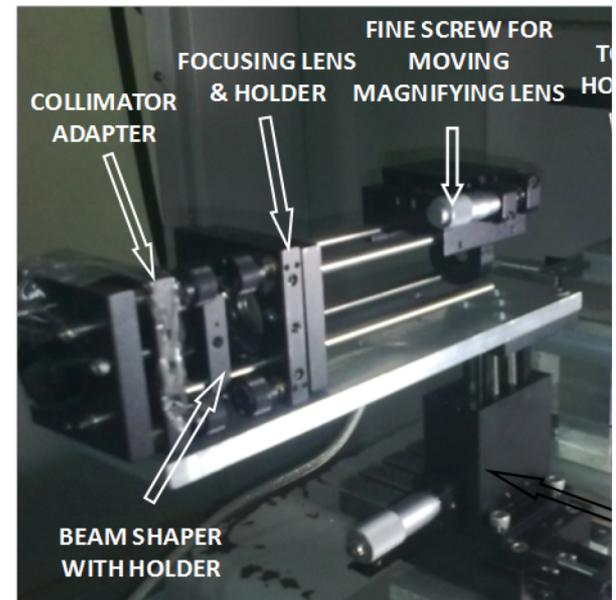
Schematic of LBM Device





Laser Setup

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



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

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

LBM (Cont.)

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

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



1. Instantaneous point heat source:

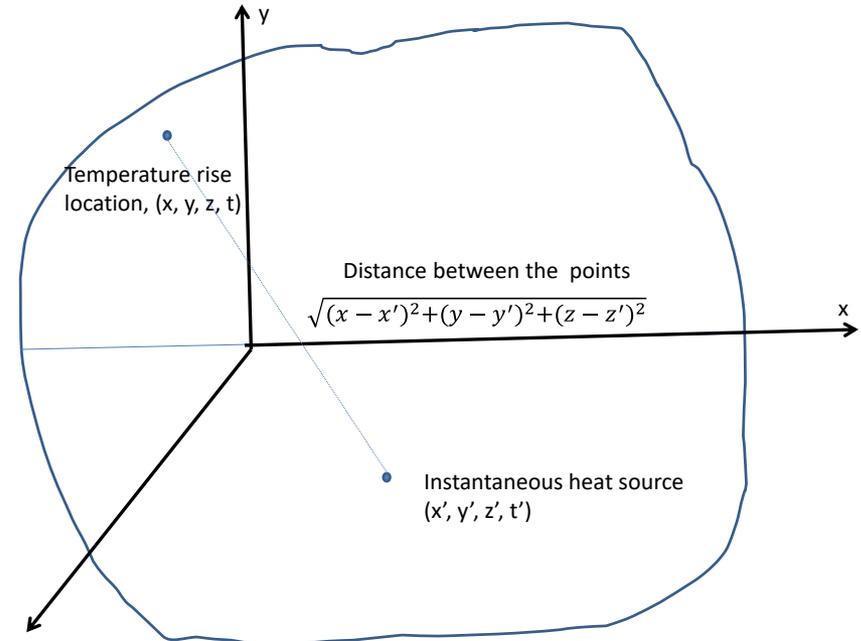
The differential equation for the conduction of heat in a stationary medium assuming no convection or radiation, is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + q = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

This is satisfied by the solution for infinite body,

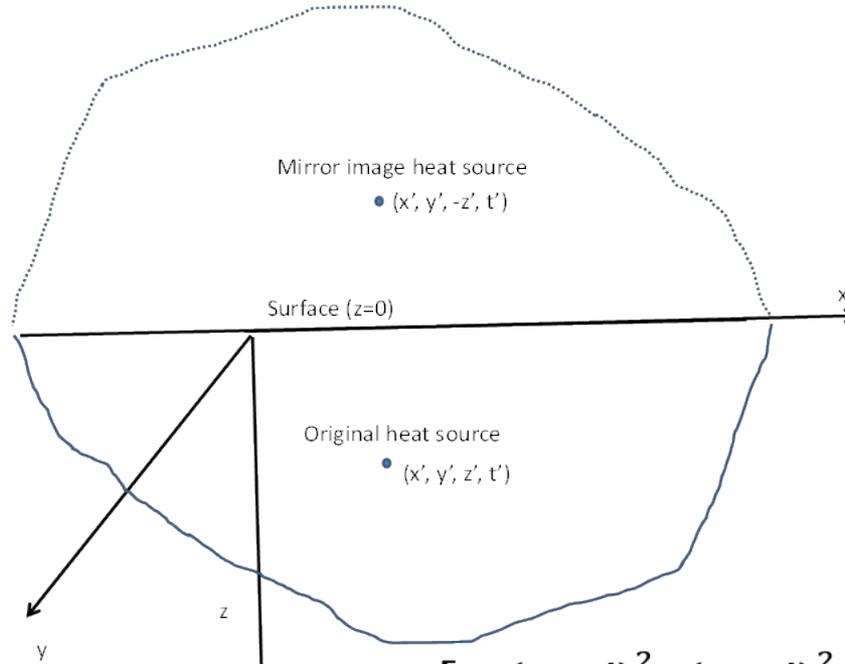
$$dT(x, y, z, t) = \frac{\delta q}{\rho C (4\pi\alpha(t-t'))^{3/2}} \exp \left[-\frac{(x-x')^2 + (y-y')^2 + (z-z')^2}{4\alpha(t-t')} \right]$$

gives the temperature rise at position (x, y, z) and time t due to an instantaneous heat source δq applied at position (x', y', z') and time t' ; where δq = instantaneous heat generated, C = sp. heat capacity, α = diffusivity, ρ = Density, t = time, K = thermal conductivity.



Temperature rise in semi-infinite body

- A mirror image can be used
- No heat transfer at the surface of semi-infinite body



$$dT(x, y, z, t) = \frac{\delta q}{\rho C (4\pi a(t-t'))^{3/2}} \exp \left[-\frac{(x-x')^2 + (y-y')^2 + (z-z')^2}{4a(t-t')} \right]$$

$$+ \frac{\delta q}{\rho C (4\pi a(t-t'))^{3/2}} \exp \left[-\frac{(x-x')^2 + (y-y')^2 + (z+z')^2}{4a(t-t')} \right]$$



Semi-infinite body

- $dT(x, y, z, t) =$

$$\frac{\delta q}{\rho C (4\pi a (t-t'))^{3/2}} \exp\left[-\frac{(x-x')^2 + (y-y')^2}{4a(t-t')}\right] \left[\exp\left[-\frac{(z-z')^2}{4a(t-t')}\right] + \exp\left[-\frac{(z+z')^2}{4a(t-t')}\right] \right]$$

- If the heat is applied at the surface or $z'=0$, such as moving area heat sources

- $dT(x, y, z, t) = \frac{2\delta q}{\rho C (4\pi a (t-t'))^{3/2}} \exp\left[-\frac{(x-x')^2 + (y-y')^2 + z^2}{4a(t-t')}\right]$



2. Continuous point heat source in infinite body:

If the heat is liberated at the rate $dQ = P \cdot dt'$ from $t = t'$ to $t = t' + dt'$ at the point (x', y', z') , the temperature at (x, y, z) at time t is found by integrating above equation, and C = sp. heat capacity, α = diffusivity, ρ = Density. From the point heat source solution,

$$dT(x, y, z, t) = \frac{P dt'}{\rho C (4\pi a (t - t'))^{\frac{3}{2}}} \exp\left[-\frac{(x - x')^2 + (y - y')^2 + (z - z')^2}{4a(t - t')}\right]$$

Now if the heat source is on from time $t' = 0$ to $t' = t$ continuously it can be written as

$$dT(x, y, z, t) = \int_{t'=0}^{t'=t} \frac{P dt'}{\rho C (4\pi a (t - t'))^{\frac{3}{2}}} \exp\left[-\frac{(x - x')^2 + (y - y')^2 + (z - z')^2}{4a(t - t')}\right]$$



Continuous point heat source

To simplify the situation, one can assume that the heat source was switched on at time, $t'=-t$ and turned off at $t'=0$

$$dT(x, y, z, t) = \int_0^t \frac{P dt}{\rho C (4\pi a(t))^{\frac{3}{2}}} \exp \left[-\frac{(x-x')^2 + (y-y')^2 + (z-z')^2}{4a(t)} \right]$$

where Q is in Watts. As $t \rightarrow \infty$ steady state temperature distribution occurs given by

$$T(x, y, z) = \frac{P}{4 \pi k \sqrt{[(x-x')^2 + (y-y')^2 + (z-z')^2]}}$$

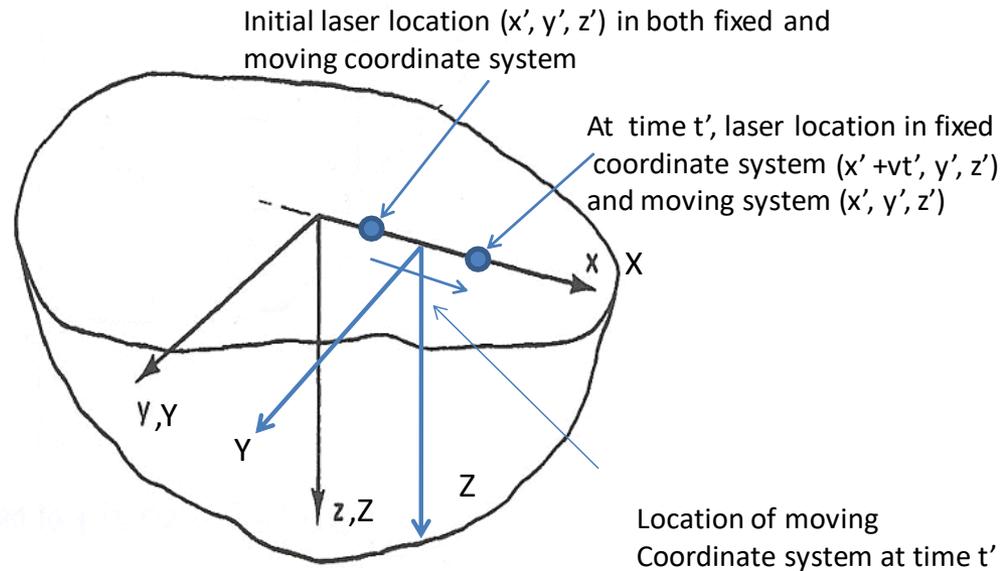


Moving heat source solution steps

- Moving heat source is in fact a continuous stationary source in moving frame of reference
- Next step is used to find the superposition of point solutions in spatial co-ordinates in moving frame of reference for obtaining, line, plane or volumetric heat source.
- Transform the solution to fixed coordinate system
- Integrate with respect to time (t') for final solution in $T(x, y, z, t)$



Moving point heat source in semi-infinite body



Moving laser source along X-axis in a semi -infinite body

In moving coordinate system:

$$dT(X, Y, Z, t) = \frac{2\delta q}{\rho C (4\pi a (t - t'))^{\frac{3}{2}}} \exp\left[-\frac{(X - x')^2 + (Y - y')^2 + (Z)^2}{4a(t - t')}\right]$$

In fixed coordinate system:

$$dT(x, y, z, t) = \frac{2\delta q}{\rho C (4\pi a (t - t'))^{\frac{3}{2}}} \exp\left[-\frac{(x - vt' - x')^2 + (y - y')^2 + (z)^2}{4a(t - t')}\right]$$

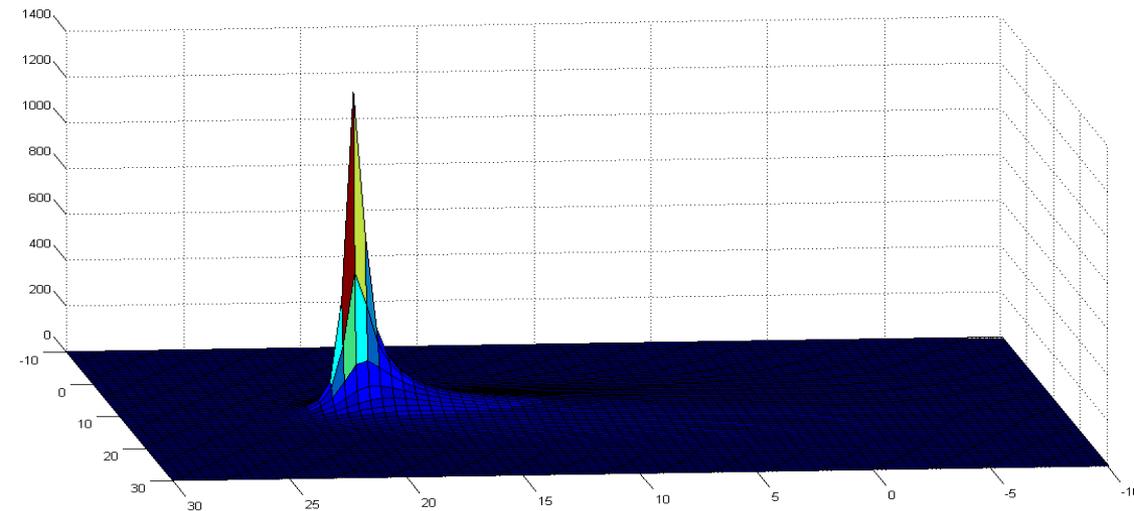


Moving point heat source:

Consider point heat source P heat units per unit time moving with velocity v on semi-infinite body from time $t'=0$ to $t'=t$. During a very short time heat released at the surface is $dQ = P dt'$. This will result in infinitesimal rise in temperature at point (x, y, z) at time t given by,

$$dT(x, y, z, t) = \int_{t'=0}^{t'=t} \frac{2P dt'}{\rho C (4\pi a(t-t'))^{\frac{3}{2}}} \exp\left[-\frac{(x-vt'-x')^2 + (y-y')^2 + (z-z')^2}{4a(t-t')}\right]$$

The total rise in of the temperature can be obtained by integrating from $t'=0$ to $t'=t$



Gaussian Circular

- Gaussian beam distribution

$$I(x', y') = \frac{2P}{\pi\sigma^2} \exp\left[-\frac{2(x'^2 + y'^2)}{\sigma^2}\right]$$

- Gaussian circular heat source



Gaussian Circular

- In moving coordinate system

$$dT(t') = \frac{4P dt'}{\pi \sigma^2 \rho C (4\pi a(t-t'))^{\frac{3}{2}}} \frac{\pi \sigma^2 4a(t-t')}{\sigma^2 + 8a(t-t')} \exp\left[-\frac{2(X^2 + Y^2)}{\sigma^2 + 8a(t-t')} + \frac{Z^2}{4a(t-t')}\right]$$

- In fixed coordinate system

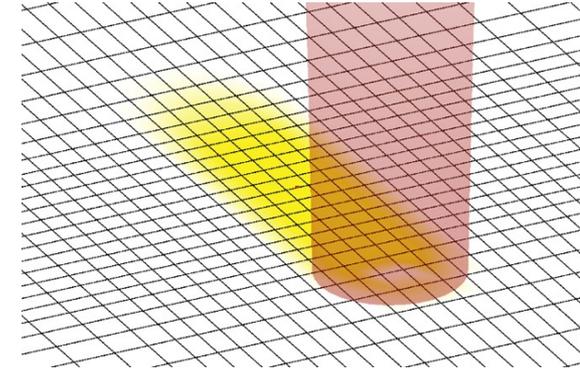
$$T - T_0 = \frac{4P}{\rho C \pi \sqrt{4a\pi}} \int_{t'=0}^{t'=t} \frac{dt' (t-t')^{-0.5}}{\sigma^2 + 8a(t-t')} \exp\left[-\frac{2((x-vt')^2 + y^2)}{\sigma^2 + 8a(t-t')} - \frac{z^2}{4a(t-t')}\right]$$



Uniform intensity:

- Uniform circular moving heat source:

In the Uniform heat source, Q is defined by the magnitude q and the distribution parameter σ . The heat distribution, Q, is given by, $I(x,y) = \frac{P}{A}$ Where $A = \pi \sigma^2$



for circular heat source integrating with space variables,

$$dT(X, Y, Z, t) = \frac{2Pdt'}{8\rho C\pi\sigma^2 (\pi a(t-t'))^{\frac{3}{2}}} \exp\left[-\frac{Z^2}{4a(t-t')}\right] \times$$

$$\int_{-\sigma}^{\sigma} \exp\left[-\frac{(X-x')^2}{4a(t-t')}\right] dx' \int_{-\sqrt{\sigma^2-x'^2}}^{\sqrt{\sigma^2-x'^2}} \exp\left[-\frac{(Y-y')^2}{4a(t-t')}\right] dy'$$

Now final temperature equation is obtained by integrating with time from 0 to t,

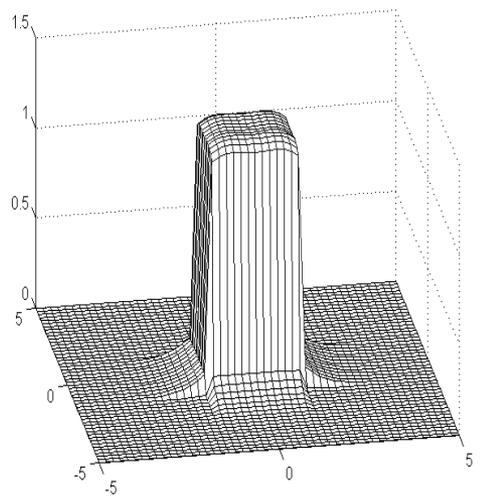


Uniform rectangular moving heat source:

Rectangular heat source of dimension $-l < y' < l$ and $-b < x' < b$ i.e. for moving with constant velocity v from time $t' = 0$ to $t' = t$.

Heat intensity I is given by, $I(x,y) = \frac{P}{A}$ where $A = 4*b*l$

Integrating with the space variables,



$$dT(X, Y, Z, t) = \frac{2Pdt'}{4bl\rho C(4\pi a(t-t'))^{\frac{3}{2}}} \exp\left[-\frac{Z^2}{4a(t-t')}\right]$$

$$\int_{-l}^l \exp\left[-\frac{(Y-y')^2}{4a(t-t')}\right] dy' \int_{-b}^b \exp\left[-\frac{(X-x')^2}{4a(t-t')}\right] dx'$$

Results can be obtained by numerical integration with respect to time.



LBM Capability

- MRR
 - Cutting speed can be as high as 4 m/min.
 - Typical material removal rate is 5 mm³/min.
- Dimensional Tolerance
 - Typical ranges from ± 0.015 - ± 0.125 mm
- Surface Finish
 - R_a varies between 0.4 – 6.3 μm .

LBM (Cont.)

- Process Variations

- Laser beam machines can be used for cutting, surface hardening, welding, drilling, blanking, engraving and trimming.
- Types of lasers used: pulsed and CW CO₂, Nd:YAG, Nd:glass, ruby and excimer.
- High-pressure gas streams are used to enhance the process by aiding the exothermic reaction process, to cool and blow away the vaporized or molten material and slag.

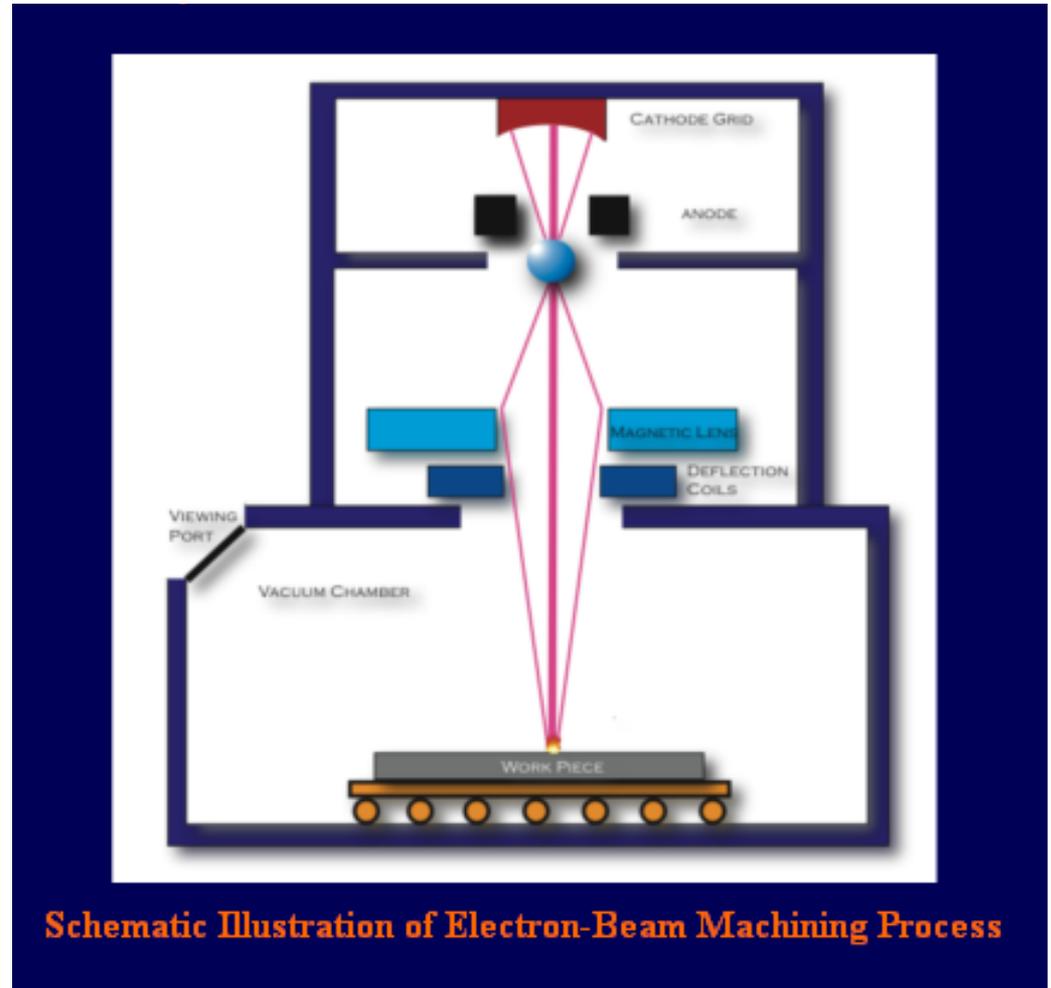
LBM (Cont.)

- Applications
 - Multiple holes in very thin and thick materials
 - Non-standard shaped holes and slots
 - Prototype parts
 - Trimming, scribing and engraving of hard materials
 - Small diameter lubrication holes
- Limitations
 - Localized thermal stresses, heat affected zones, recast layer and thermal distribution in thin parts
 - Difficulty of material processing depends on how close materials boiling and melting points are
 - Hole wall geometry can be irregular
 - The cutting of flammable materials is usually inert gas assisted

Electron-Beam Machining (EBM)

How it Works

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

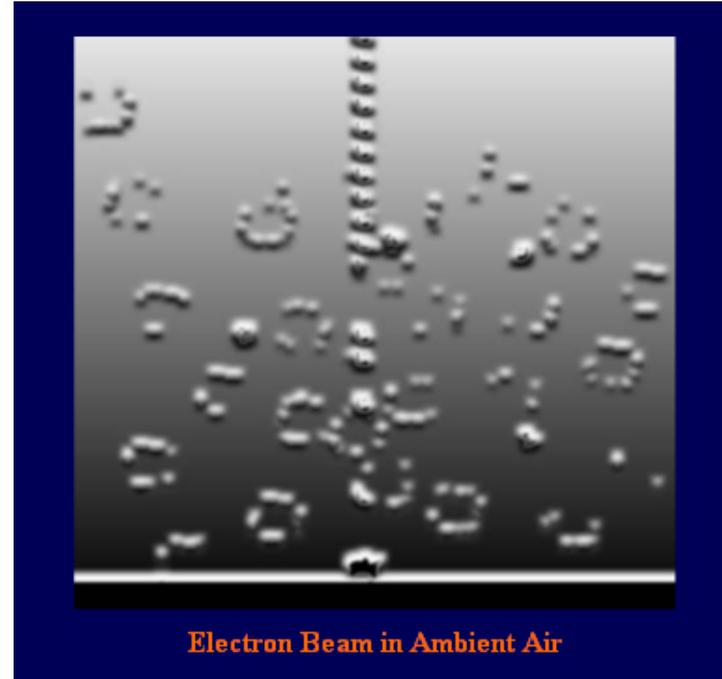
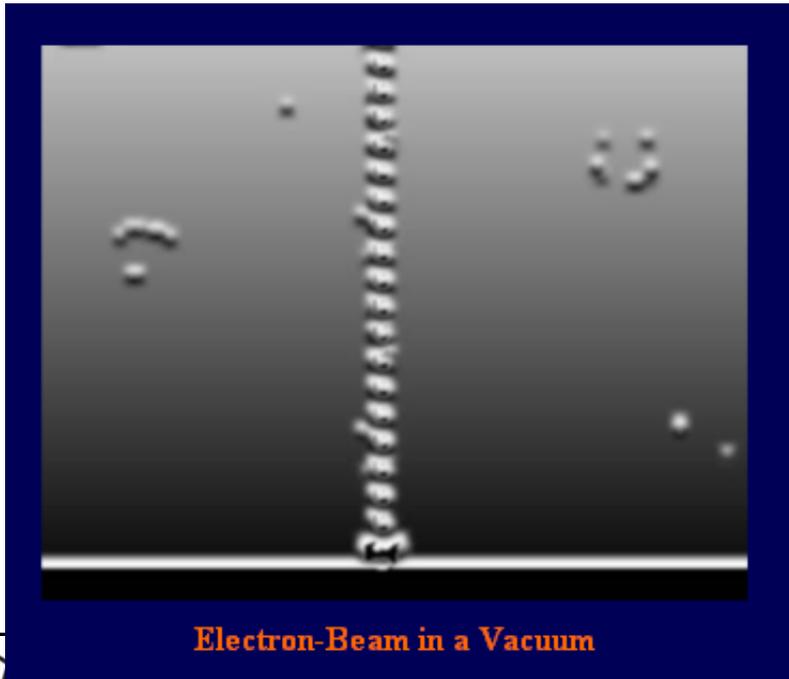


Schematic Illustration of Electron-Beam Machining Process



EBM (Cont.)

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



EBM Characteristics

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



Comparative Performance

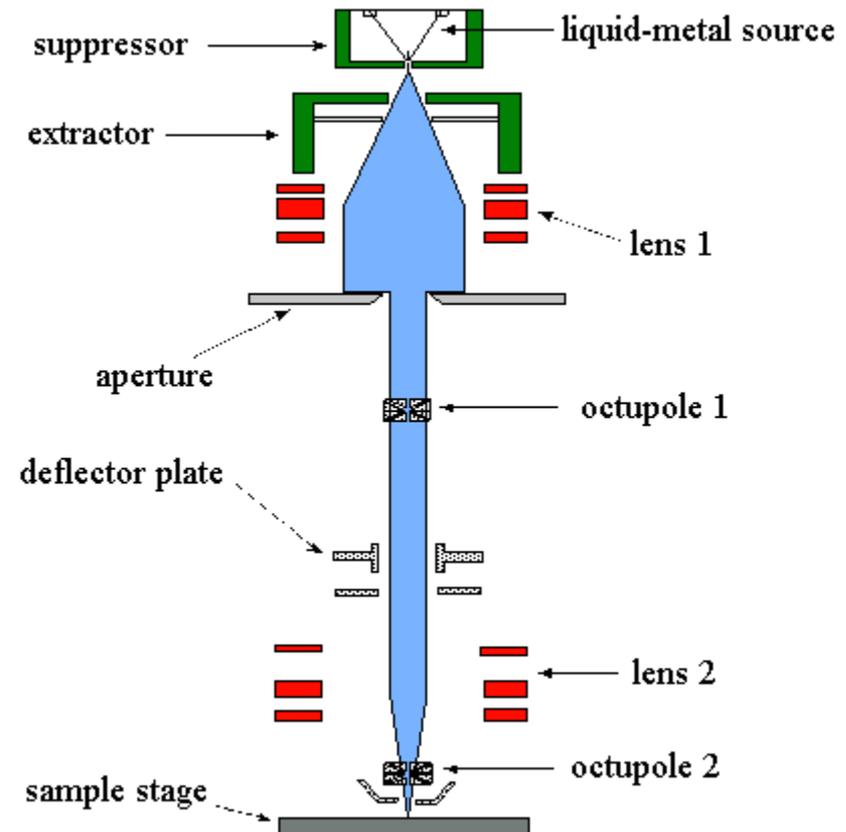
Process	Metal removal rate (cm ³ /s)	Approximate unit power (specific cutting energy) (GJ/m ³)	Relative capital equipment cost per unit material removal rate
Edge-tool machining	14	3	1
Abrasive machining	8	30	2
Plasma jet	1.5	10	—
ECM	1.0	500	60
EDM	0.10	150	40
Ultrasonic machining	0.005	150	600
Electron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

^aAdapted from Wager [18].

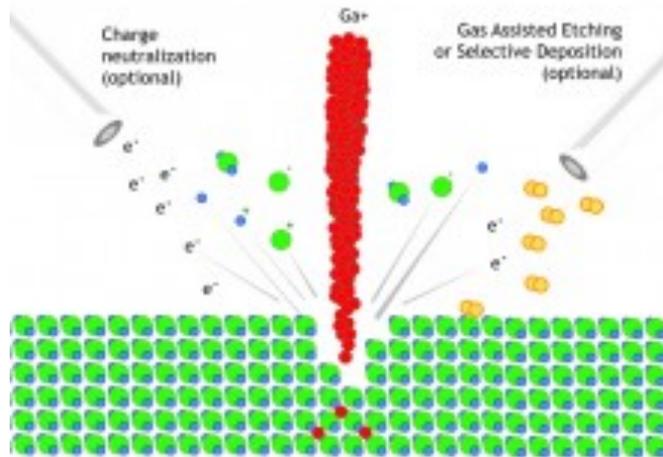


Focused Ion Beam Technologies

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



Mechanism



Rate of etch depth

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

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



Dual Beam System

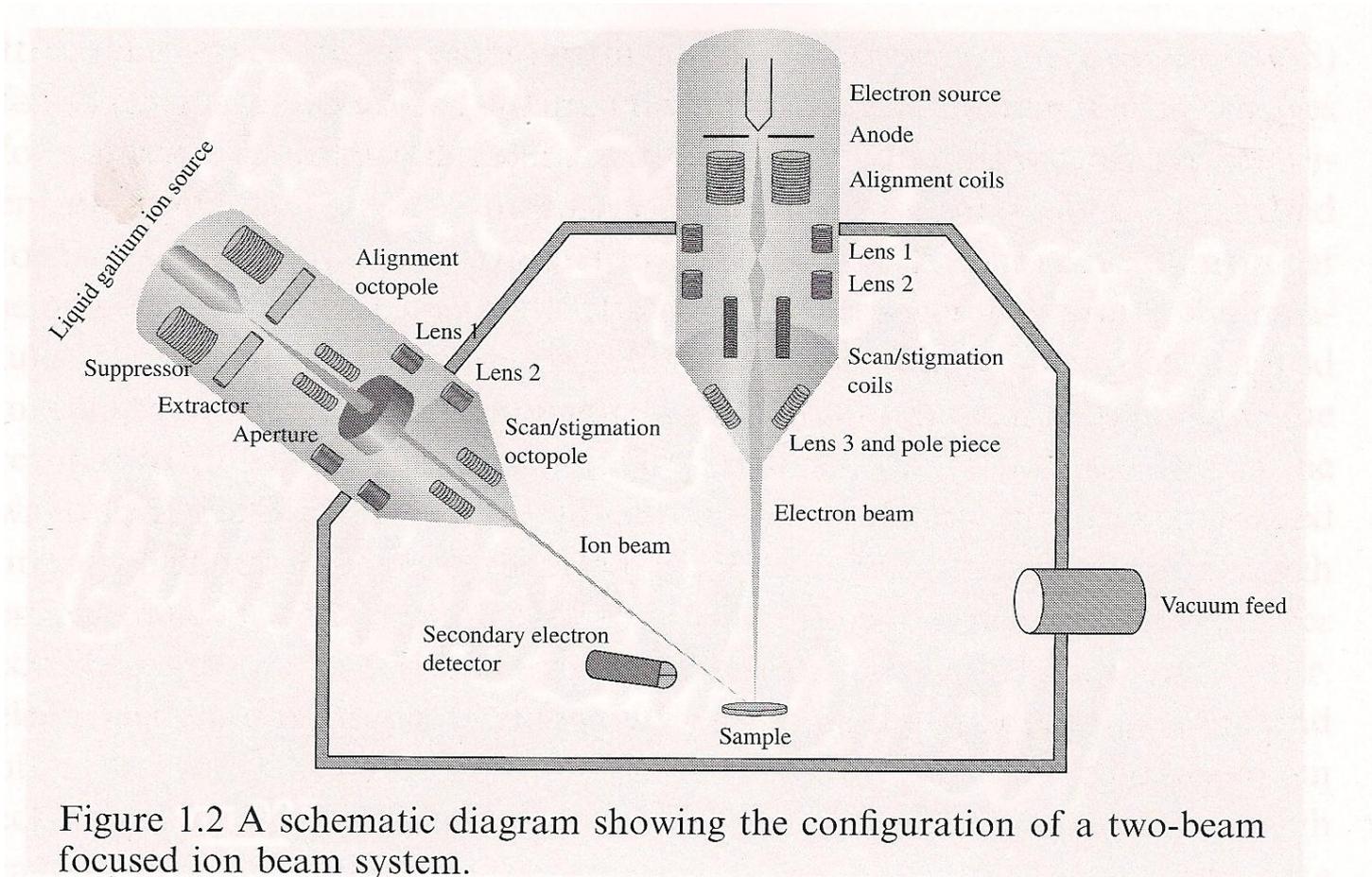


Table 1.1 *Quantitative comparison of FIB ions and SEM electrons*

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



Focused Ion Beam Technologies

- FIB finds application in:
 - Ablation of hard materials: diamond, WC
 - Polishing of single crystals
 - Deposition
 - Site-specific analysis
 - FIB lithography
 - TEM samples
- Capital investment ~ 5 Crore



Process Capabilities of FIB

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



Summary

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

