Non-Traditional Manufacturing Processes (NTMP)

Lecture 5 and 6: Electron Beam Machining

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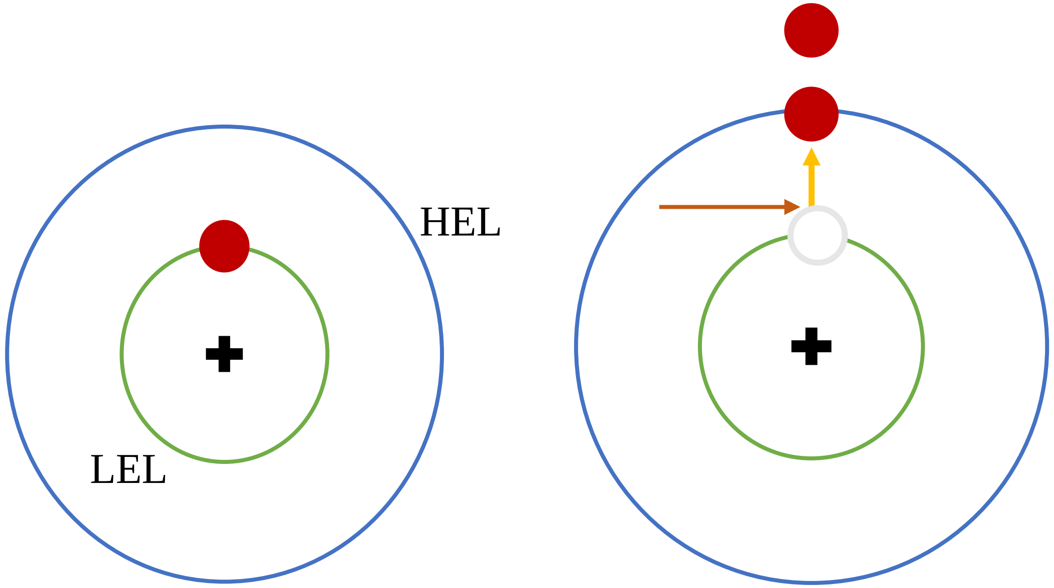
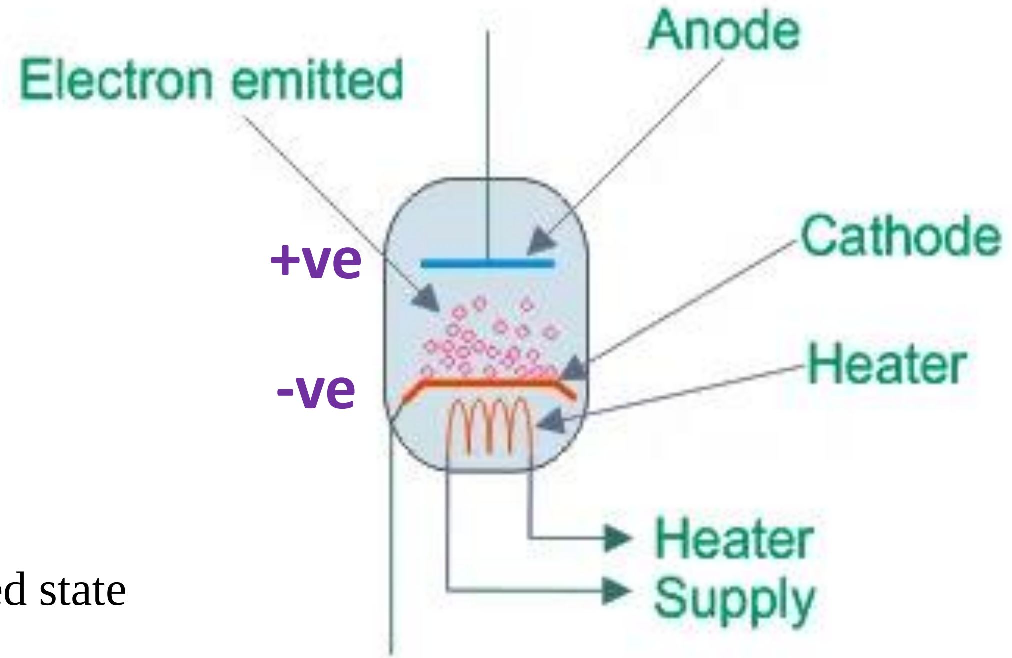
Electron Beam Machining (EBM)

- Electron beam is used for machining.
- Electrons are generated by **thermionic emission from hot tungsten cathode**.
- Thermionic emission : emission of electrons from an electrode due to its temperature.

thermal energy provided to the charge carrier > work function of the material (binding potential).





LEL: Lower energy level/ Ground state, HEL: Higher energy level/ Excited state

: electron , : Thermal energy,

Fig. Schematic of thermionic emission process

Electron Beam Machining (EBM)

- Electron Beam Machining (Drilling) was first introduced in 1952 and EBW was introduced in industry in 1959.

- Spot diameter: 10- 200 μm and Power density = 6500 billion W/mm^2 = 6.5×10^{12} W/mm^2
- Any material can rapidly melt and vaporize.
- EBM is a very precise vaporization process.

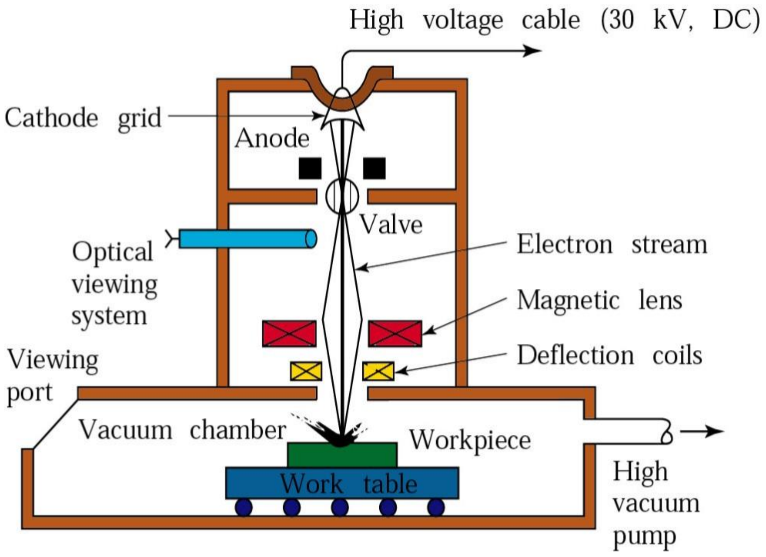
- **Basic Process:** EBM - Thermal process, similar to LBM.

Material-heating: Striking of high-velocity electrons with workpiece.

Kinetic energy of electrons $\Rightarrow$ Heat $\Rightarrow$ Rapid melting and vaporizing

Electron Beam Machining (EBM)

- **Applications: Drilling fine holes, cutting narrow slots,** welding, annealing, milling, and rapid manufacturing by controlling various operating parameters



- Electron beam processing: Usually done in vacuum unlike LBM.

In atmosphere: Frequent collisions with air molecules

Lateral dispersion due to Scattering, Energy loss,

Reduction in Power density at the work piece.

- **High Power with High Accelerating Voltage E-Beam – Used in normal Atmosphere**

Mechanism of Electron Beam Machining (EBM)

Change in Kinetic Energy of Electron = $m_e(u - u_o)^2/2$ eV, u (km/s) ~ $600\sqrt{(V)}$
$m_e = 9.1 \times 10^{-31}$ kg, e = 1.6×10^{-19} Coulomb.
KE is dissipated in the impinging material.

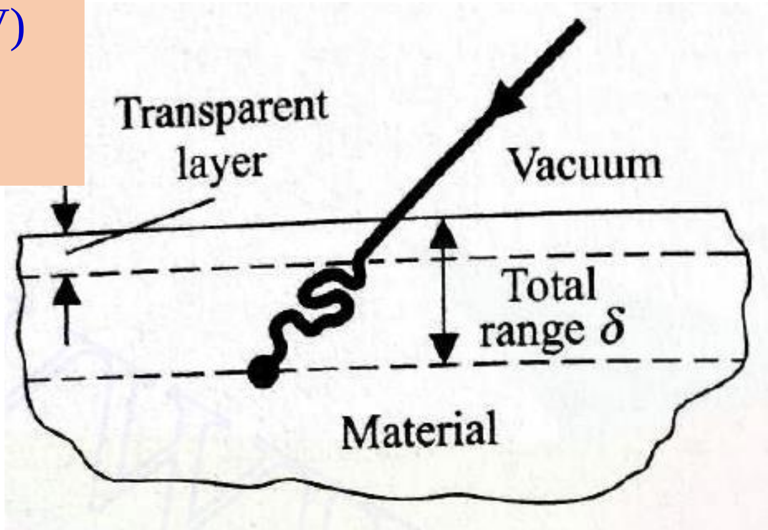


Figure: Movement of an electron below surface

* Unaffected zone: Transparent layer
* Energy of Electrons → Lattice of material through collisions.
* Energy transfer → Function of kinetic energy or accelerating voltage.

- Maximum rise in temperature- At a certain depth, not at the surface, unlike laser heating.

Depth of penetration:
$\delta = 2.6 \times 10^{-17}(V^2/\rho)$ mm
where,
V=Accelerating voltage (Volts) and
ρ = Material density (kg/mm^3)

Power requirement for machining:
P = CQ
where,
C = Constant of proportionality or specific power consumption in EBM , and Q = Material removal rate

Numerical

Q. What will be the penetration depth of the electron beam accelerated at 150 kV impinging in steel having density of 76×10^{-7} kg/mm^3?

Solution: $$\delta = 2.6 \text{ x}10^{-17}(V^2/\rho) \text{ mm}$$

$$\delta = 77 \ \mu\text{m}$$

Q. An electron beam of 5 kW power is used for cutting a 150 µm wide slot in 1 mm thick tungsten sheet. Determine the cutting speed?

(Specific power consumption in EBM (constant of proportionality) for tungsten is 12 W/mm^3/min)

Solution: $$P = CQ$$

Let the speed of cutting be V mm/min.

$$Q = AV = 150 \times 10^{-3} \times 1 \times V \text{ mm}^3/\text{min}$$

$$P = C_{Tungusten}\, Q$$

$$5000 = 12 \times 150 \times 10^{-3} \times 1 \times V$$

$$V = 2778 \text{ mm/min} = 4.6 \text{ cm/sec}$$

Electron Beam Drilling Process: Four Stages

1. **Localized heating of work-piece:** On an organic or synthetic backing

* E-beam focal spot diameter ≤ Desired diameter

* Power density : ~10^8 W/cm^2, sufficient to melt & vaporize any material.

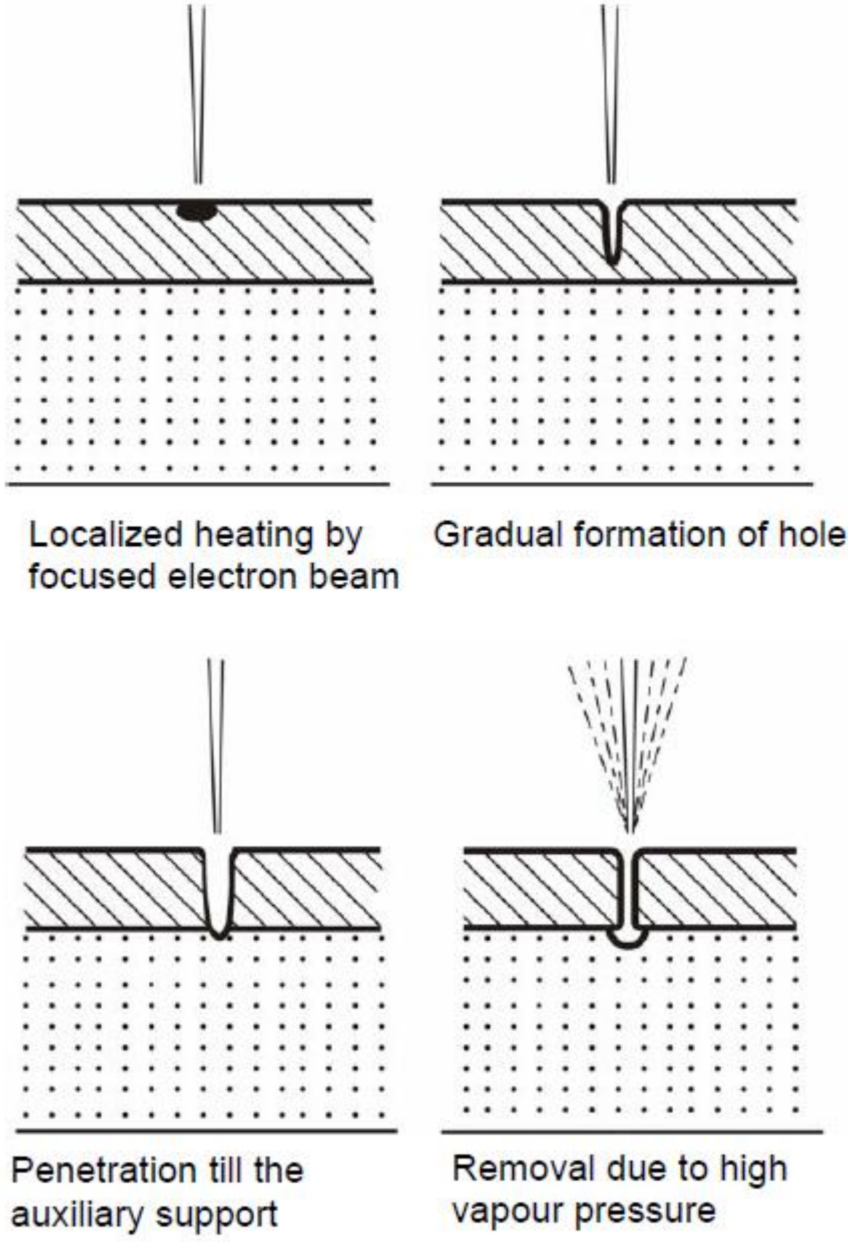
2. **Vaporization of a small fraction of melted material**

- Recoil pressure of escaping vapour pushes the molten material aside creating a hole.

3. **E-beam penetrates in till it reaches the bottom surface of work piece.**

4. **Removal of material:** As e-beam strikes the auxiliary support volume in contact is totally vaporized resulting in the explosive release of backing material vapour

* High velocity vapour carries along with it the molten walls of the capillary, creating a hole in the work piece and a small cavity in the backing material.



Components of Electron Beam Machining

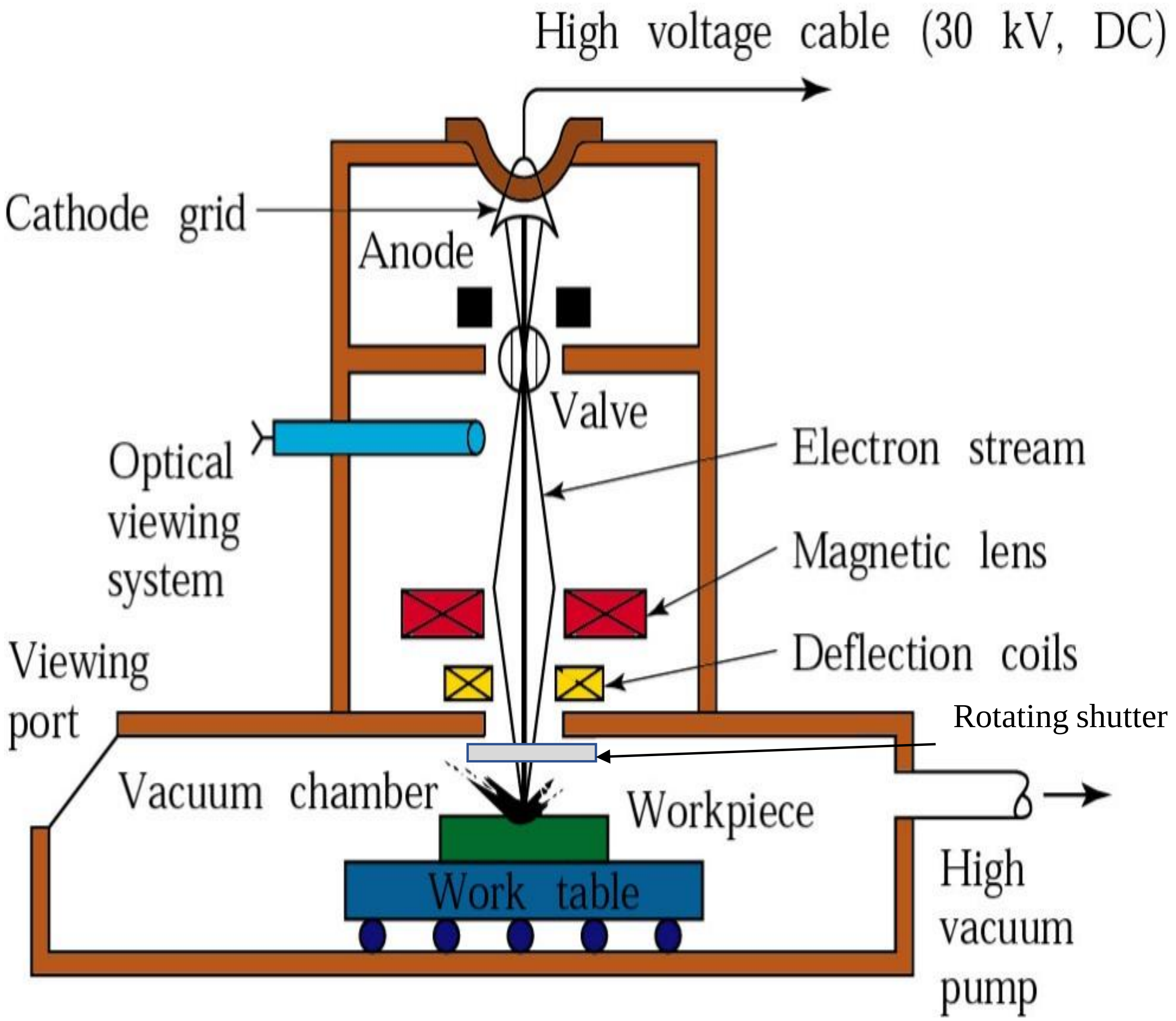
Electron beam gun: Electrons are generated by thermionic emission from hot tungsten cathode.

In E-beam gun for cutting & drilling applications, there is a grid between anode & cathode on which negative voltage is applied to pulse / modulate the e-beam.

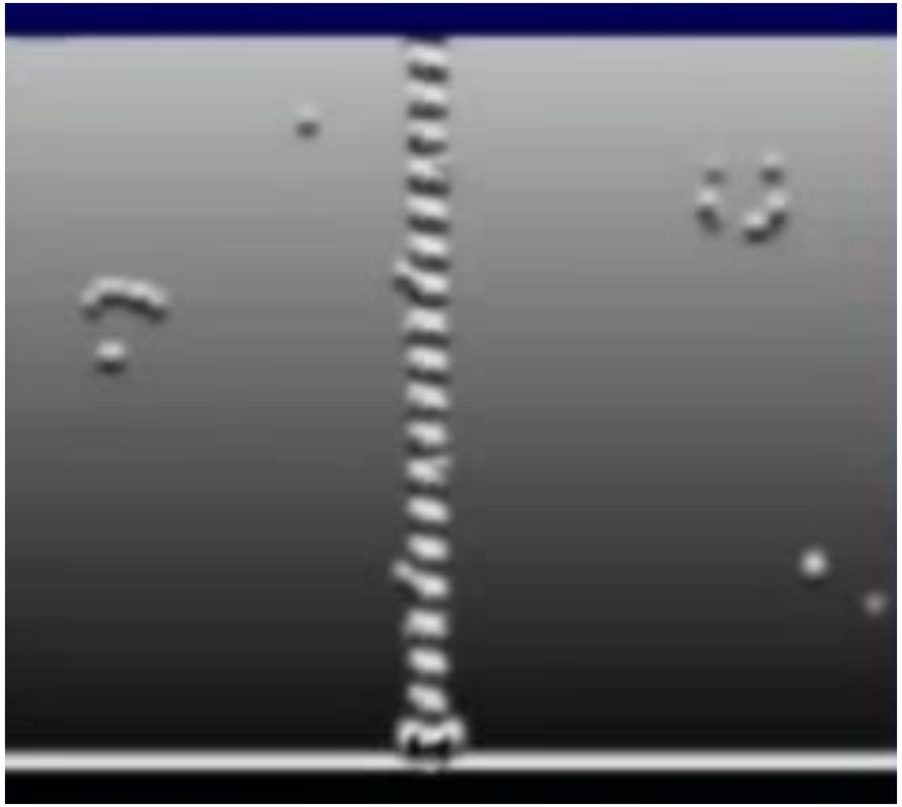
Power supply: Up to 150 kV, Current : 150 µA-1.5A.

Vacuum-chamber: 10^{-4}-10^{-6} Torr (1 Torr = 1 mm Hg) achieved by rotary pump backed diffusion pump.

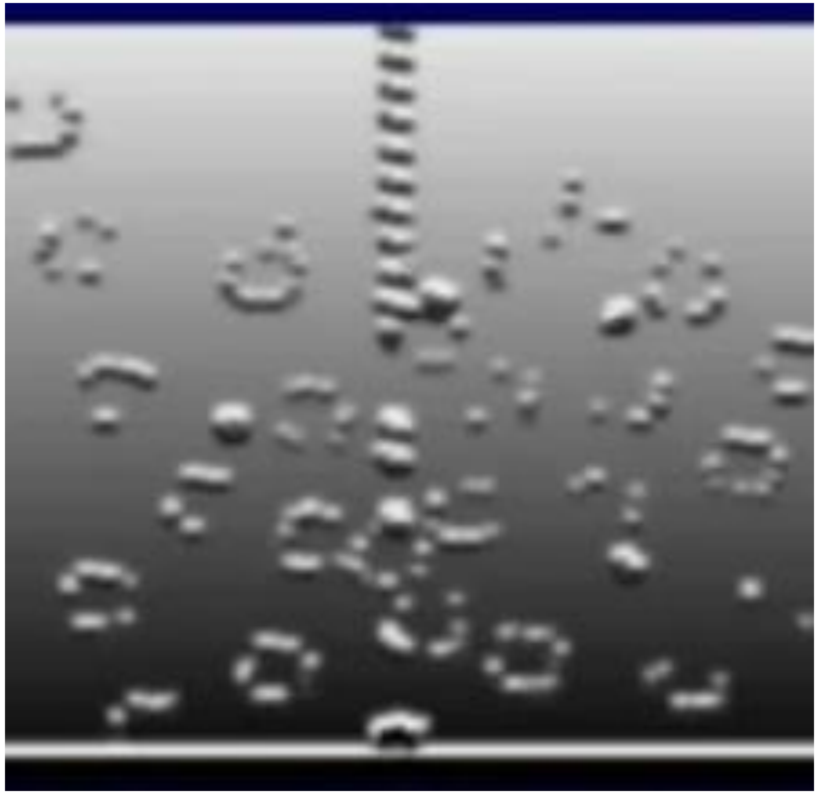
Vacuum compatible **CNC workstation**



Requirement of Vacuum in EBM



Electron beam in vacuum



Electron beam in ambient air

Diffusion Pump

- Diffusion pump is essentially an oil heater.
- As the oil is heated the oil vapour rushes upward. The nozzles change the direction of motion of the oil vapour and the oil vapour starts moving downward at a high velocity as jet.
- Such high velocity jets of oil vapour traps any air molecules present within the gun through diffusion.
- The oil vapour condenses due to presence of cooling water jacket around the diffusion pump. Redirected back to the boiler and recycled.
- Builds high pressure at the bottom and low pressure at the top.

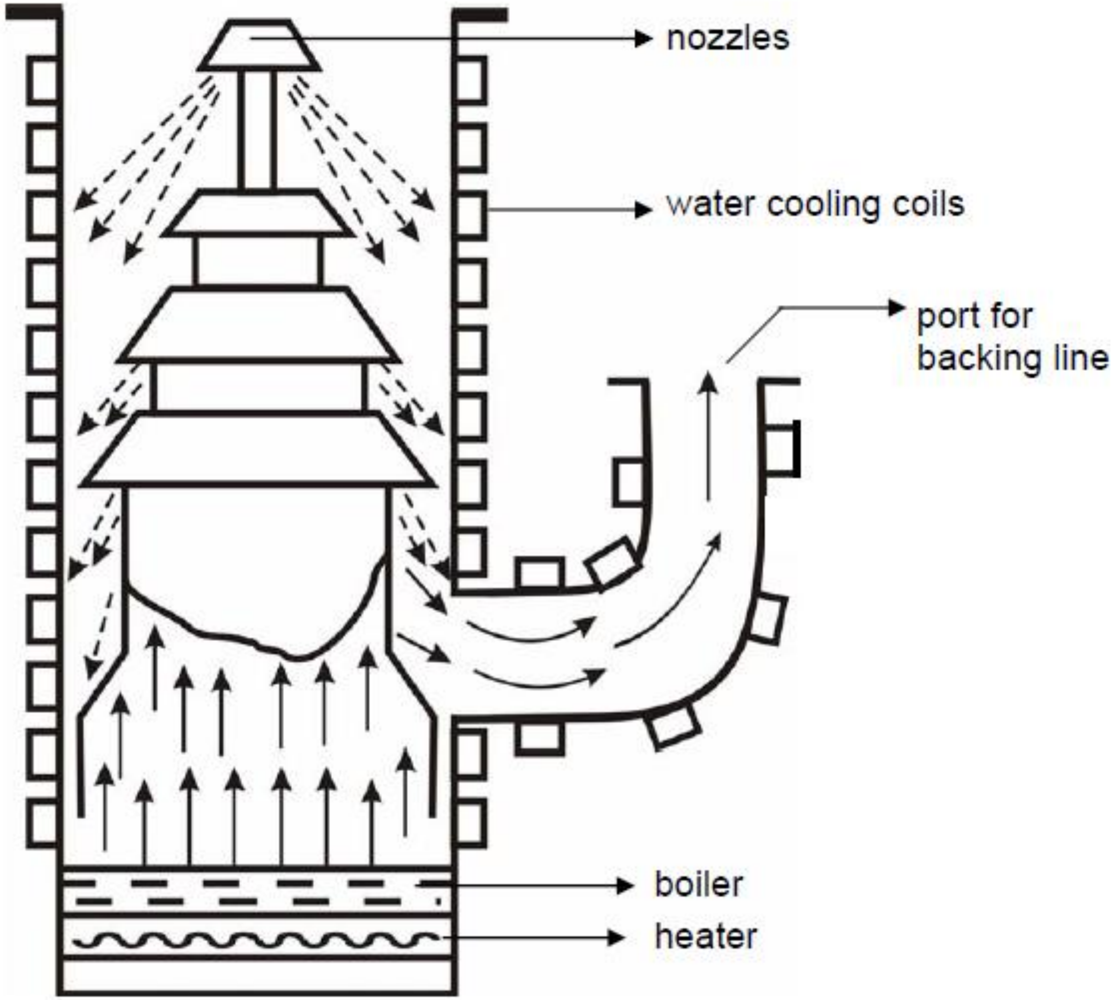


Fig. Working of a diffusion pump

Current Control in EBM

- Hot cathode emits electrons under vacuumed condition, and the thermionic emission is given by the Richardson- Dushman equation:

$$j = A\,T^2 \exp(-eW/kT)$$

Nobel prize in physics in 1928

where,

j = Emission current density (amp/cm^2) from the cathode surface

W = Work function of the cathode material (Volts)

T = Absolute Temperature of cathode (K)

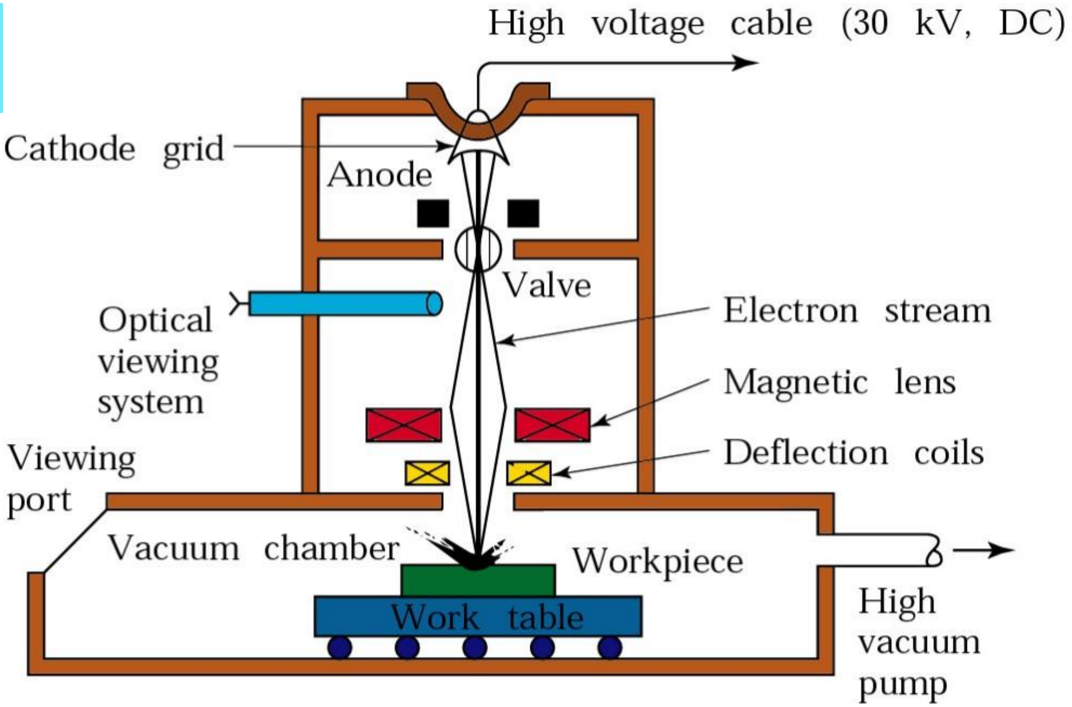
e = Electron charge (Coulomb)

k = Boltzmann constant (1.3×10^{-23} J/K)

A = Constant (~120 Amp/cm^2.K^2)

- Cathode Material: Tungsten or thoriated tungsten

Process Parameters of EBM



The process parameters, which directly affect the machining characteristics in EBM are:

- Accelerating Voltage
- E-Beam Current
- Pulse duration
- Energy per pulse
- Peak power
- Lens used- determines the focusing & focal length
- Spot size
- Beam deflection signal
- Beam power density
- Vacuum level in the machine

Typical Process Parameters:

Electron Acceleration Voltage : 10-150 kV
Electron beam current : 100 µA – 1.5A
Electron beam Power delivered
(Accelerating Voltage x Beam Current) : 30 W-100 kW
Process Medium /Environment : Vacuum, 10^{-4}-10^{-6} Torr (mm of Hg)

Beam Energy is increased preferably by increasing current than accelerating voltage to avoid more scattering at higher electron energy.

Energy Balance in EBM

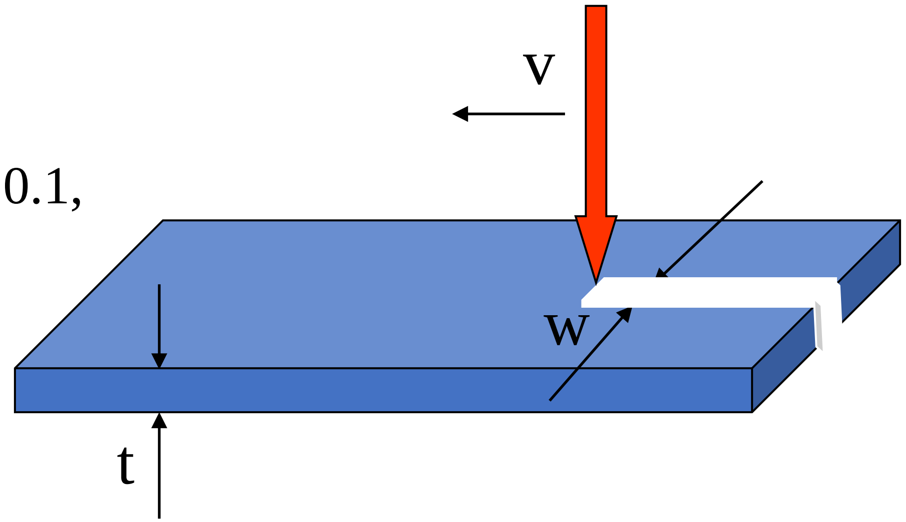
Energy balancing:

(mass flow rate ($\dot{m}$) = density * area * velocity)

$$\eta P = \dot{m}\,(C_p\,\Delta T)$$

$$\eta P = w.t.v.\rho.C_p.\,\Delta T$$

w= kerf width ≈ Thermal diffusion length ≈ $2\sqrt{\alpha\tau} = 2\sqrt{\alpha d/v}$



Where, η =E- beam power coupling efficiency including conduction loss ≈ 0.1,

P = E-beam power in W;

t= depth of penetration in m up to which rise in temperature is ΔT,

α = Thermal diffusivity = $k/\rho.\,C_p$

k= Thermal conductivity of material in W/m.ºC

ρ =Material density in g/m^3; C_p = Specific heat in J/kg. ºC;

τ = E-beam material interaction time

(For continuous e-beam scanned at velocity, v interaction time, τ = d/v)

d= width of e-beam in m;

v= Processing speed in m/s

Numerical

Q: In a 1 mm tungsten sheet a 200 micron wide slot is to be cut using a 4kW electron beam. Estimate the maximum cutting speed.

ρ = 19300 kg/m^3, C_p = 140 J/kg ºC, L_f = 185 kJ/kg

L_v= 4020 kJ/kg, α = 164W/mºC, T_v = 5930 ºC, η= 0.1

Solution:

w= 200 micron, t = 1mm, P = 4kW,

$w = 2\sqrt{\alpha d/v}$ **---------------(1)**

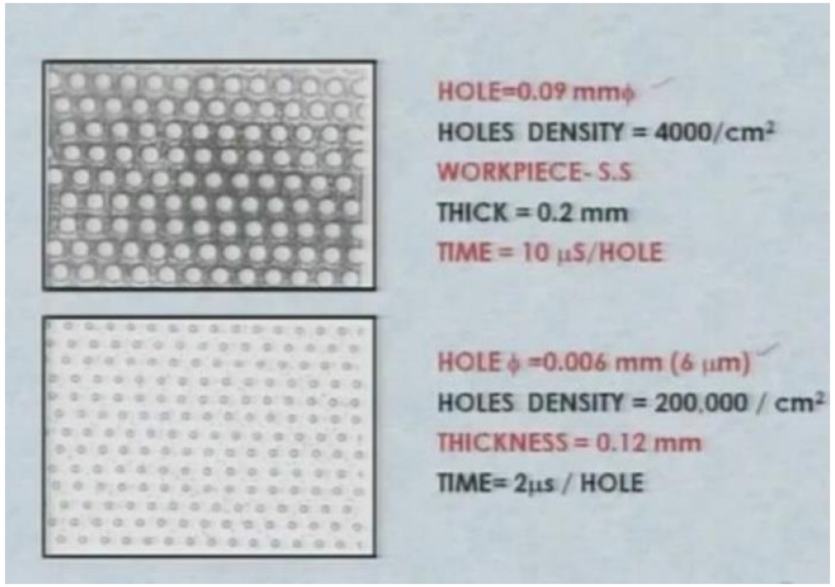
$\eta P = w.t.v.\rho.C_p.\Delta T$--------------------(2)

We need to solve for d & v

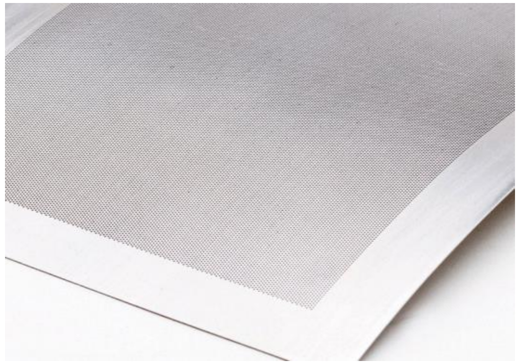
Applications of EBM

EB Drilling: Suitable where large no. of holes are needed and drilling holes with conventional process is difficult due to material hardness or hole-geometry.

- Used in aerospace, instrumentation, food , chemical & textile industries.
- Thousands of tiny holes in Turbine (steel) engine combustor.
- Cobalt alloy fiber spinning heads.
- Filters used in food processing.
- Perforation in artificial leather to make shoes for air-breathing: 0.12 mm hole made at 5000/s.



Insulation
Centrifugal disc for glass wool production
12000 to 45000 holes
https://www.pro-beam.com/en/contractmanufacturing/mikrobohren



Sieves for food industry
12 million holes /m^2
1805 holes/sec

Process Capabilities

- A wide range of materials, such as stainless steel, Cu, Al, Ni and cobalt alloys, super alloy, titanium, tungsten, ceramic, leather and plastic.
- Cutting up to a thickness of 10 mm : *material removal by vaporization*
- Hole-diameter ranging from 0.1- 1.4 mm and thickness up to 10 mm. High aspect (depth to diameter) 15:1
- Holes at angle ranging from 20º -90º
- No much force to the work-piece, thereby allowing brittle and fragile materials to be processed without danger of fracturing.
- Hole diameter accuracy ± 0.02 mm in thin sheets

Advantages of EBM

Drilling & Cutting

- Any material can be machined
- No cutting forces are involved so no stresses imposed on part
- Exceptional drilling speeds possible with high position accuracy
- Extremely small kerf width, less wastage of material
- Less mechanical or thermal distortion
- Computer-controlled parameters
- High aspect ratio
- High accuracy

Limitations of EBM

- High capital cost and maintenance cost
- Non-productive pump down time
- Recast at the edges
- High level of operator skill required
- Maximum thickness in cutting (~ 10 mm)
- A suitable backing material must be used
- Ferrous material to be demagnetized as otherwise could affect the e-beam
- Work area must be under a vacuum – Size restriction

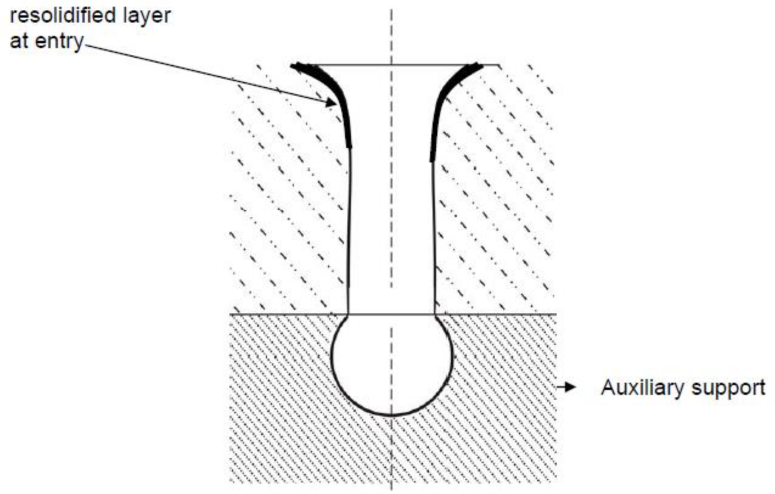


Fig. Typical kerf shape of electron beam drilled hole

Summary of EBM

Mechanics of material removal	Melting, Vaporization
Medium	Vacuum (10^{-4}-10^{-6} Torr), Air with high power, high voltage beam (not yet commercialized)
Tool	High velocity electron beam
Maximum material removal rate	~ 50 mm^3/min
Specific power consumption	450 W/mm^3 -min
Critical Parameters	Accelerating voltage, beam current, beam diameter, work speed, melting temperature
Material applications	All materials
Shape applications	Drilling fine holes, contour cutting, cutting narrow slots
Limitations	High specific energy, Necessity of vacuum, Very high machine cost.

Thank You!