Electron Beam Machining

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

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

Drilling, cutting, slotting, 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

* Energy of Electrons ⇒ Electrons and lattice of material through collisions.

* Energy transfer⇒ Function of electron energy/ accelerating voltage.

e-energy⇑, Transfer rate ⇓

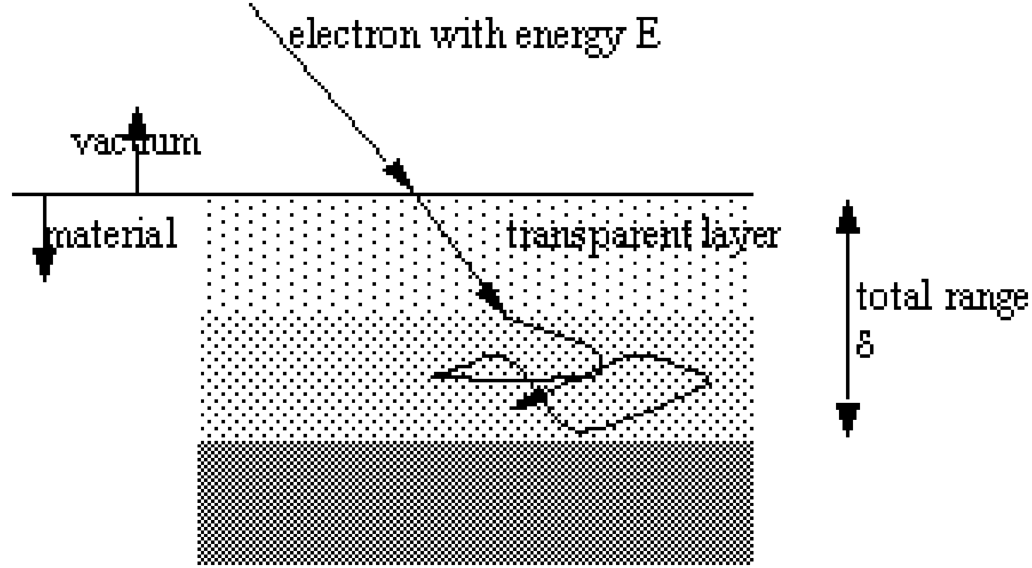
* Maximum rise in temperature- At a certain depth, not at the surface, unlike laser heating.

* Due to scattering of electrons, its energy not localized within the area determined by the diameter of beam – Poor material removal efficiency

Typical range: V=50kV,
ρ = 8000 kg/m^3

$\delta \approx 8 \mu m$

Electron Velocity=10-50% of Light velocity



Depth of penetration:

$$\delta = 2.6 \times 10^{-5} (V^2/\rho)\ \mu m$$

V=Accelerating Voltage (Volts)

ρ= Material density (kg/m^3)

Kinetic Energy of Electron

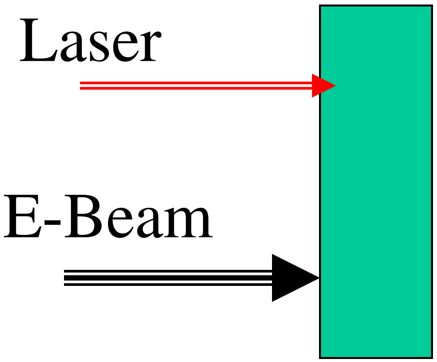
$$= m_e.c^2 [\{1/(1-(v/c)^2)^{1/2}\}-1] = e.V$$

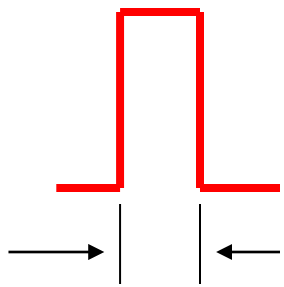
$\Rightarrow$ v (km/s) ~ $600V^{1/2}$

$m_e = 9.1 \times 10^{-31}$kg, $e = 1.6 \times 10^{-19}$Coulomb.

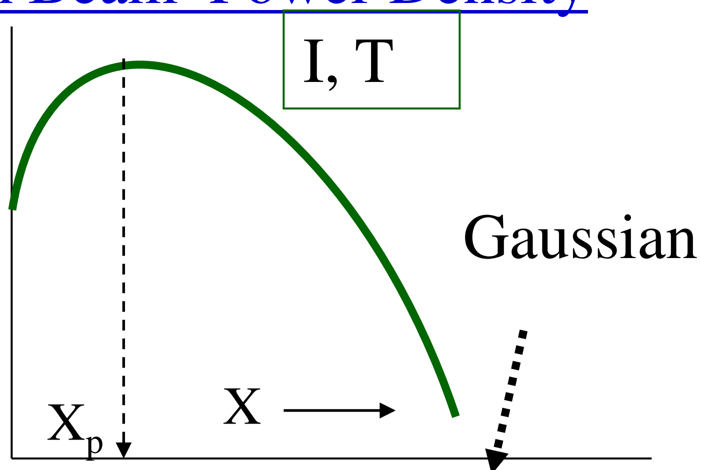
KE is dissipated in the impinging material.

Electron Beam Coupling verses Laser Beam Coupling





Electron Beam Power Density



$I(x,t) = I_0(t)(1-R_e)\ \exp\{-2(x-x_p)^2/\sigma^2\}$

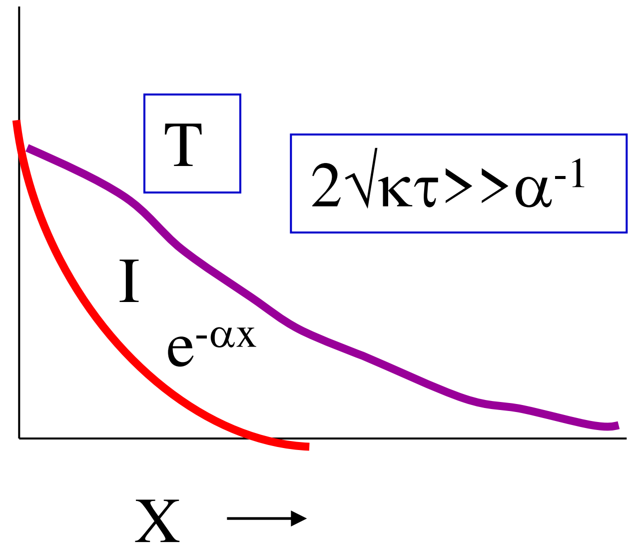
x_p & σ (width) are functions of Atomic mass of material and Electron beam energy.

$\sigma \approx \delta$ (penetration depth)

x_p & σ both increase with e-beam energy

Laser Power Density

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



Laser Power absorbed within

$d_{dif} = 2\sqrt{\kappa\tau}$

during the pulse ‘τ’

mech14.weebly.com

Electron Beam Machine

Four sub-systems

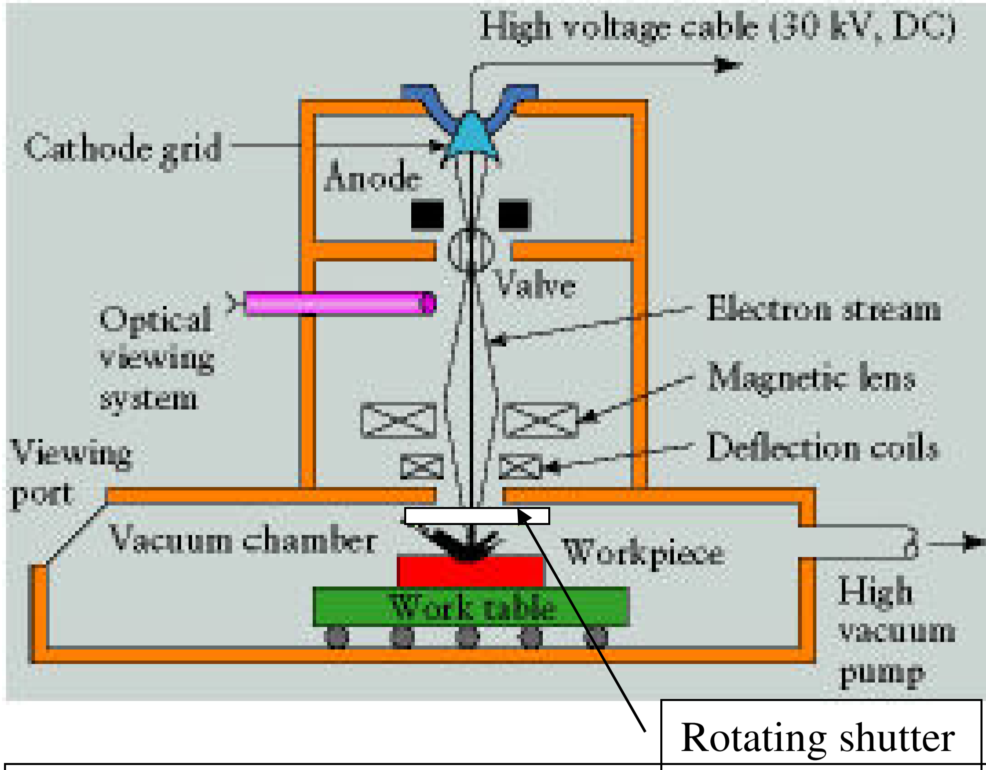
Electron beam gun: Electrons are generated by thermionic emission from hot tungsten cathode.

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 150kV, Current : 150μA-1.5A.

Vacuum-chamber: 10^{-4}-10^{-6} Torr achieved by rotary pump backed diffusion pump.

Vacuum compatible **CNC workstation**



Mode of E-beam Operation:

For drilling and cutting-Pulsed electron beam
Single pulse : A single hole in thin sheet;
Multiple pulses: To drill in a thicker material.

For welding : DC electron beam
Parameters so chosen that loss of material due to vaporization is minimum.

Current Control:

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

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

Where

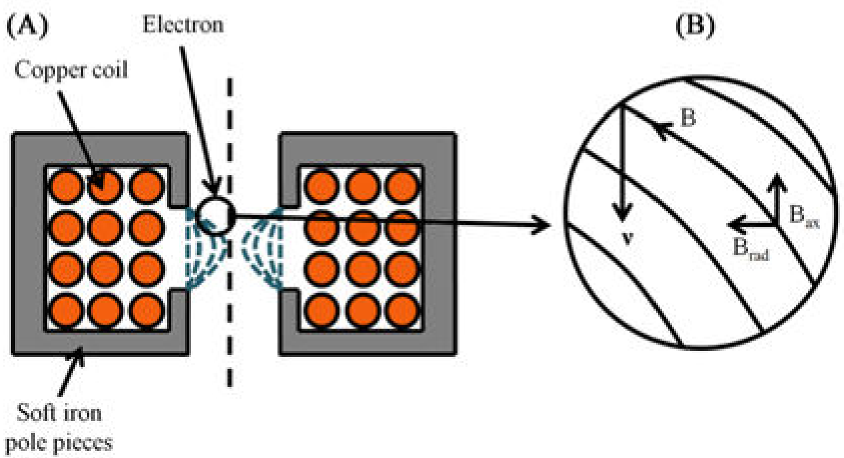
j = Current density (amp/cm^2) from the cathode surface
W = Work function of the cathode material (Volts)
T = Absolute Temperature of cathode (K)
e = Electron charge (Coulomb)
k = Boltzmann constant ($1.3\text{x}10^{-23}$ J/K)
A = Constant (~120Amp/cm^2.K^2)

Temperature $T \Uparrow$ - $j \Uparrow$

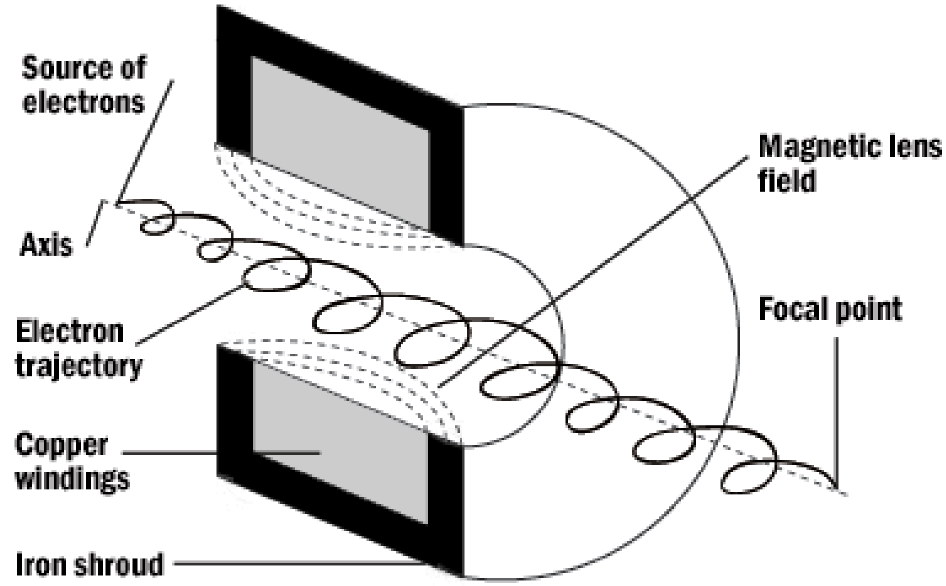
Electrons emitted from cathode are in thermal equilibrium at temperature T and their velocity is govern by Maxwellian distribution. This is reflected in focusing the electrons on the work-piece.

Cathode Material: Tungsten or thoriated tungsten

Electron paths in magnetic lens: Electron paths are usually represented by straight lines running through a convex lens. More accurately, however, the electron paths form a tight spiral as they are accelerated through the lenses. The path and trajectory taken by the electrons are influenced by the lens current as they pass though a small opening in the lens.



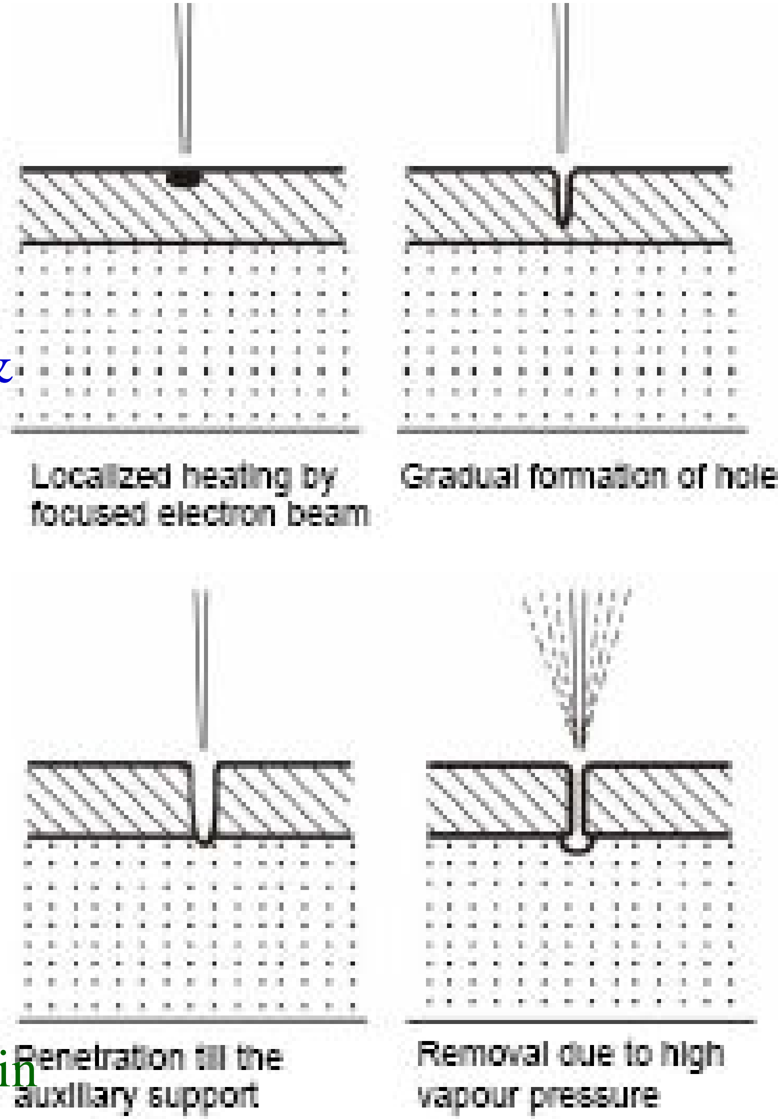
Lorentz force: $F = q\ (v \times B)$



http://nptel.ac.in/courses/102103044/module3/lec17/4.htm

https://cmrf.research.uiowa.edu/transmission-electron-microscopy

Electron Beam Drilling Process: Four Stages.



1. Work-piece: On an organic or synthetic backing

* E-beam focal spot diameter ≤ Desired diameter
* Power density : ~10^8W/cm^2, sufficient to melt & vaporize materials of any thermal conductivity

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. 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 cavern in the backing material.

Electron Beam Process Parameters:

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 current which determines the focusing & focal length
- ✓ Spot size
- ✓ Beam deflection signal
- ✓ Beam power density
- ✓ Vacuum level in the machine

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

Typical Process Parameters:

Electron Acceleration Voltage : 10-150kV

Electron beam current : 100μA – 1.5A

Electron beam Power delivered
(Accelerating Voltage x Beam Current) : 30W-100kW

Process Medium /Environment : Vacuum, 10^{-4}-10^{-6} Torr (mm of Hg)

Wavelength λ of an electron of a velocity V:

$$\lambda = \frac{h}{\left\{2mV_e e(1+eV_e/2mc^2)\right\}^{1/2}}$$

At acceleration voltage V_e=120kV, λ=0.0336Å ≈0.0034 nm

where h – Planck's constant, m_e – electron mass, e-electron charge & V_e is accelerating voltage

Similar to the laser beam, the theoretical limit of the focal spot diameter ~ λ

However, the actual focal spot size is influenced by

(a) Focal length of magnetic lens (No. of turns and current in magnetic coil)
(b) e-beam divergence (from electron gun)
(c) Mutual repulsion between electrons
(d) Spherical aberration of lens and
(e) Spread in electron velocity (Temperature dependent)
(f) Electron- Accelerating Voltage
(g) Electron-current density

Typical spot diameter for e-beam cutting, drilling & welding: μm - mm.

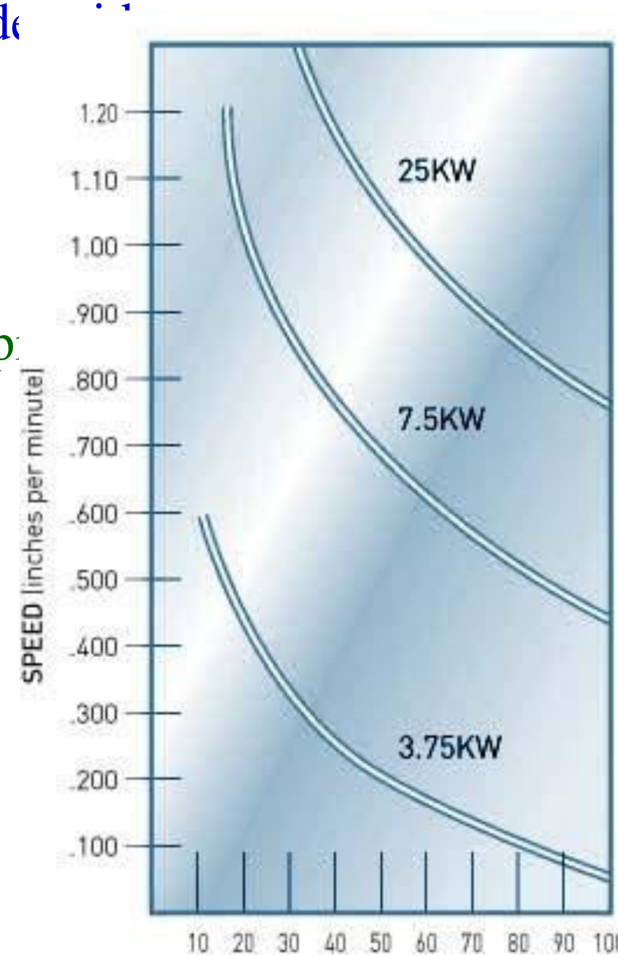
In electron beam lithography: Low current E- beam is focused down to a few nms.

Pulse mode operation- Pulse duration: 50μs - 15ms
by controlling modulation voltage on the biased cathode

Beam pulse duration ⥣ ⇒ Pulse energy ⥣
⇒ Depth and Diameter in drilling ⥣

Beam current: 100 μA -to 1A
⇒ Pulse energy ⥣

Energy in excess of 120J/pulse can be delivered and rap
drilling of very deep and large hole are obtained.



Weld depth →

Lens current: Determines the focal point of electron gun (the working distance) and the size of the focused spot on the work piece.

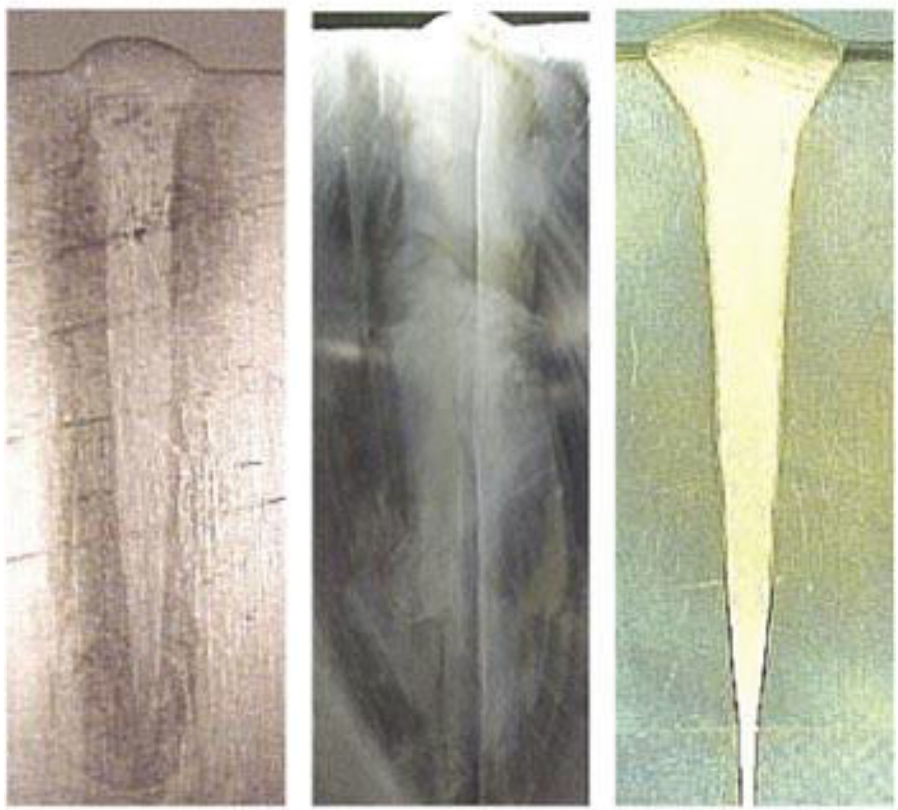
Lens current ⥣ ⇒ Focal distance & Spot size ⥥

Tapered, straight, inversely tapered,
and bell-shaped holes by adjusting the location of the focal point with respect to the top-surface of the work-piece

Hole of non-circular shape by deflecting the beam by energizing the deflection coil. Beam deflection is limited **within ~6mm**.

E- Beam Welding Speeds/ Depth of Penetration

25KW Output Typical Autogeneous (no filler added) Welds



Aluminum [2.250] (Not Maximized) | Carbon Steel 6" total–double sided -3.250" per side | Inconel 718 2.375" Depth (Not Maximized)

Numerical Problems:

1. Estimate the penetration depth of electron beam accelerated at 100kV impinging in steel having density of 7.6g/cc.

$$\delta = 2.6 \times 10^{-17} (V^2/\rho) \text{ mm}, \quad V \text{ in Volts } \& \ \rho \text{ in kg/mm}^3$$

$$\delta = 0.034 \mu m$$

2. Electron Beam power required is proportional to material removal rate: P =C.Q where C is constant of proportionality called “Specific power” i.e. Electron beam power per unit material removal rate & Q is MRR in mm^3 /min.

Typical Specific Power requirements for cutting various materials are,

Material	C ($W/mm^3/min$)
Tungsten	12
Fe	7
Ti	6
Al	4

Problem: Determine the cutting speed to cut a 250 micron wide slot in a 0.5mm thick tungsten sheet using a 1kW electron beam

$C = P/Q \Rightarrow 12 \ W/mm^3/min = 1000W / (250 \times 10^{-3} \times 0.5 \times V \text{ in mm/min})$

$V \text{ in mm/min} = 1000/(12 \times 0.25 \times 0.5) = 667 mm/min \approx 11 mm/s$

Temperature along depth for two different accelerating voltages, V_1 & V_2

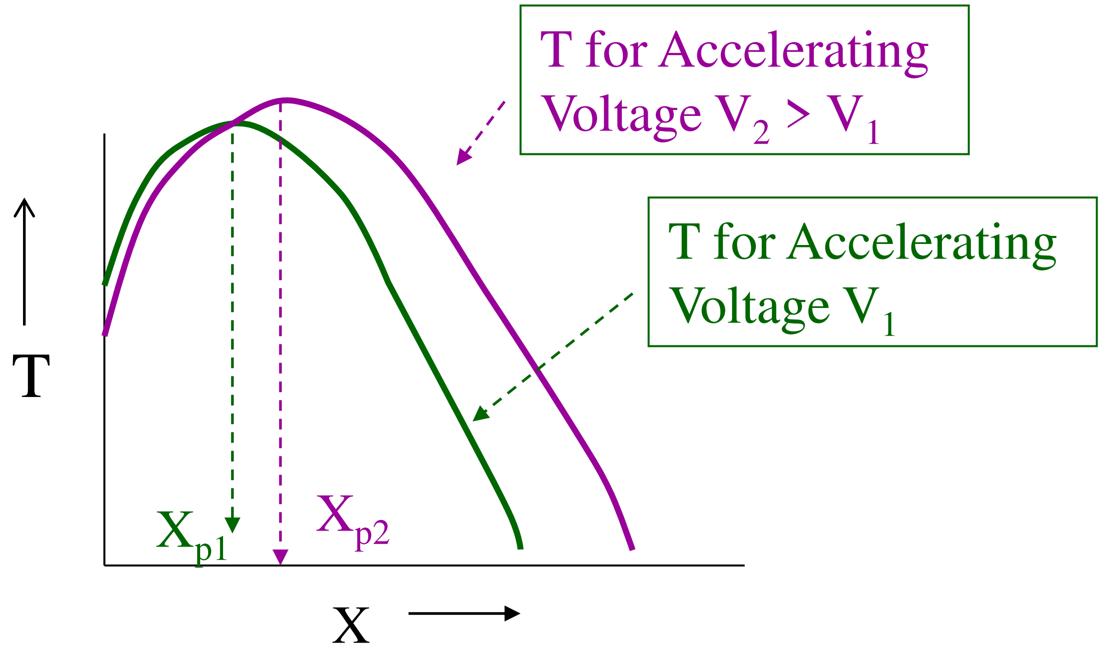
For $V_2 > V_1$

E-beam penetration depth,
$\delta_2 > \delta_1$

Distance from top surface for Peak temperature,
$X_{p2} > X_{p1}$

Width of temperature profile,
$\sigma_2 > \sigma_1$

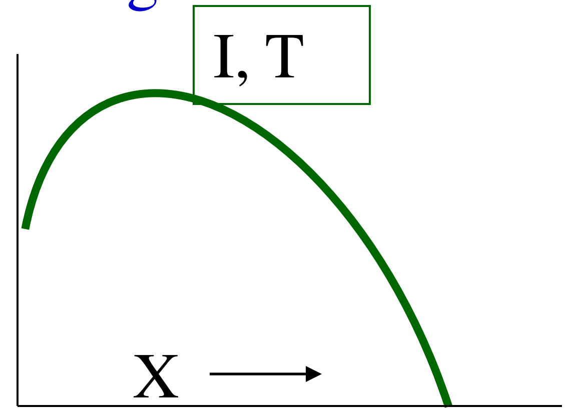
Peak temperature
$T_2 > T_1$



Heat conduction equation for Electron Beam processing:

$$k\partial^2T/\partial x^2 + H(x,t) = \rho.C_p\,\partial T/\partial t$$

$$H(x,t) = I_0(t)\,(1-R_e)\{\exp-2(x-x_p)^2/\sigma^2\}$$



To be solved numerically!!

Energy balance equation:

$$\eta P = w.t.v.\ \rho.\{C_p.\ \Delta T_b+L_f+m'.L_v\} = w.t.v.\ \rho.C_p.\ \Delta T^* \quad \text{----(1)}$$

where, $\Delta T^* = \Delta T_b+(L_f+m'.L_v)/C_p$

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

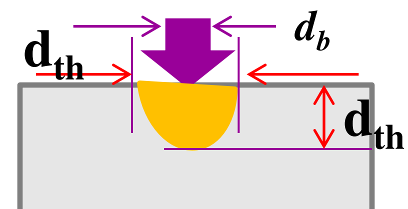
P = E-beam power; t= depth of penetration up to which rise in temperature is ΔT_b,

v= processing /scan speed, w = kerf-width, κ. = Thermal diffusivity = k/ ρ. C_p ;

k= Thermal conductivity, ρ=Material density ; C_p = Specific heart ;

ΔT_b= Temperature rise to boiling point

E-beam is usually focused to a very small spot and the thermal diffusion could be significant., i.e. it could determine the kerf-width in cutting or hole diameter in drilling. Therefore, thermal diffusion length , d_{th} needs to be compared with the e-beam spot diameter, d_b



Thermal diffusion length, d_{th} $= 2\sqrt{(\kappa.\tau)} = 2\sqrt{(\kappa.d_b/v)}$ --(2)

Where, τ = E-beam material interaction time . For continuous e-beam scanned at velocity, v interaction time, $\tau = d_b/v$, d_b= width of e-beam in m;

From (1) & (2), for $d_{th} > d_b$, $w = d_{th}$

$$\Delta T^* = \eta P / \{2t(k.d.v.\rho.C_p)^{1/2}\}$$ ***Otherwise if $d_{th} < d_b$, $w = d_b$ in Eq.1***

Example: In a 1mm tungsten sheet a 200 micron wide slot is to be cut using a 50 kW electron beam. Estimate the maximum cutting speed.

$\rho = 19300 kg/m^3$, $C_p = 140 J/kg^\circ C$, $L_f = 185 kJ/kg$

$L_v = 4020 kJ/kg$, $k = 164 W/m.^\circ C$, $T_v = 5930^0 C$, $\eta \approx 0.1$

W= 200 micron

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

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

We need to solve for d &v

Ans:

V= 2.88 m/s, d= 200micron

Process Capabilities :

EBM:

* 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 10mm : *material removal by vaporization*
* Hole-diameter ranging from 0.1- 1.4mm in thickness up to 10mm.
* High aspect (depth to diameter) 15:1
* Holes at very shallow angle from 20^0-90^0
* No much force to the work-piece, thereby allowing brittle and fragile materials to be processed without danger of fracturing.
* Hole diameter accuracy $\pm$ 0.02mm in thin sheets

EBW (welding):

* Deep penetration welding up 300mm in high (10^{-6}Torr)vacuum, 50mm (10^{-4}Torr)
* High depth to width aspect ratio 10-25:1
* Various weld geometry: Butt, Lap, T- joints
* Owing to very high power density a wide range of metals can be welded: steel, copper, nickel based alloys, aluminum alloys and refractory such as zirconium, tantalum, titanium and niobium.

Application Examples:

EB Drilling: Suitable where large no. of holes is to be drilled
where 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 (0.1- 0.9$\pm$0.05mm) in
Turbine (steel) engine combustor.
Cobalt alloy fiber spinning heads.
Filters & Screens used in food processing.

Perforation in artificial leather to make shoes for air-breathing: 0.12mm hole made at 5000/s.

EBW: Welding with minimum distortion- Finished components
Parts of target pistols,
Bimetal strips,
Dissimilar metals,
Aircraft gas turbine components,
Automobile catalytic converter, etc.

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 and form
- ✓ Extremely small kerf width, little wastage of material
- ✓ Little mechanical or thermal distortion
- ✓ Computer-controlled parameters
- ✓ High aspect ratio
- ✓ High accuracy

EBW (welding)

- ✓ Minimum thermal input
- ✓ Minimum HAZ & Shrinkage
- ✓ High aspect ratio & Deep penetration
- ✓ High purity, no contamination
- ✓ Welds high-conductivity materials

Disadvantages of EBM :

- High capital cost
- Nonproductive pump down time
- Recast at the edges
- High level of operator skill required
- Maximum thickness that can be cut about 10mm (3/8”)
- 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

- High joint preparation & tooling costs for welding
- X-ray shielding required
- Seam tracking sometimes difficult.

E-Beam Welding in Air

High Power and High Accelerating Voltage

Air Temperature ⇑, Air density⇓, Beam Dispersion minimum

Experimental results :

E-beam energy = 50-60kW, Voltage -150-175kV

Stand off distance =1-5cm

304 Steel Welding : Butt Joint Thickness 50mm

Welding Speed = 1-7cm/s ⇒ Low heat conduction loss

Weld width ⇓ with Welding Speed

⇒ Higher Efficiency up to 55%

Summary of EBM Characteristics:

Mechanics of material removal	:	Melting, Vaporization
Medium	:	Vacuum (10^{-4}-10^{-6} Torr), Air with high power, high Voltage beam (not yet commercially popular)
Tool	:	High velocity electron beam
Maximum material removal rate	:	~$50 mm^3$/min
Specific cutting energy	:	~$1500 J/mm^3$
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.