Advanced Machining Processes

ME-688

MED Elective Course

Electron Beam Machining

by

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- Introduction
- The Virtue of Electrons
- Electron's Emission
- Electron Beam Gun
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- EB Drilling
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EB based Machining: Introduction

In EB machining an electrical energy is used to generate a focused beam of electrons with high energy, which in turn generate thermal energy for removing the material from the surface of metal. This process is best suited for the micro-cutting of materials.

Application of EBM :

1. EBM is mainly used for micro-machining operations on thin materials. These operations include drilling, slotting, and scribing, etc.
2. Micro-drilling operations (up to 0.002 mm) for thin orifices, dies for wire drawing, parts of electron microscopes, injector nozzles for diesel engines, etc.
3. A micromachining technique known as “Electron beam lithography” is being used in the manufacture of field emission cathodes, integrated circuits, and computer memories.

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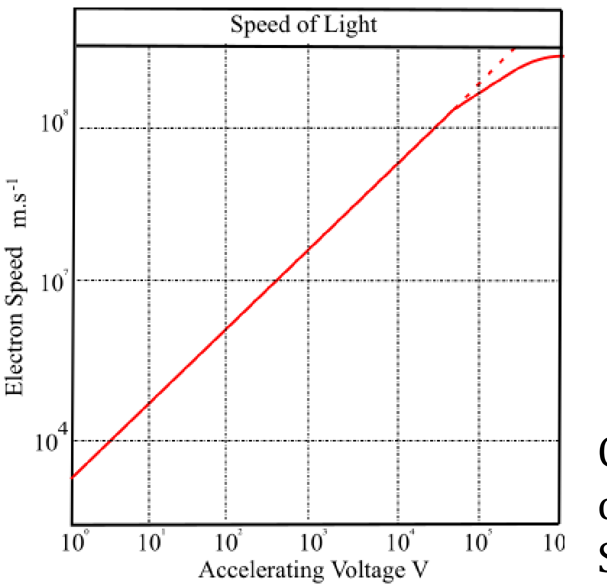
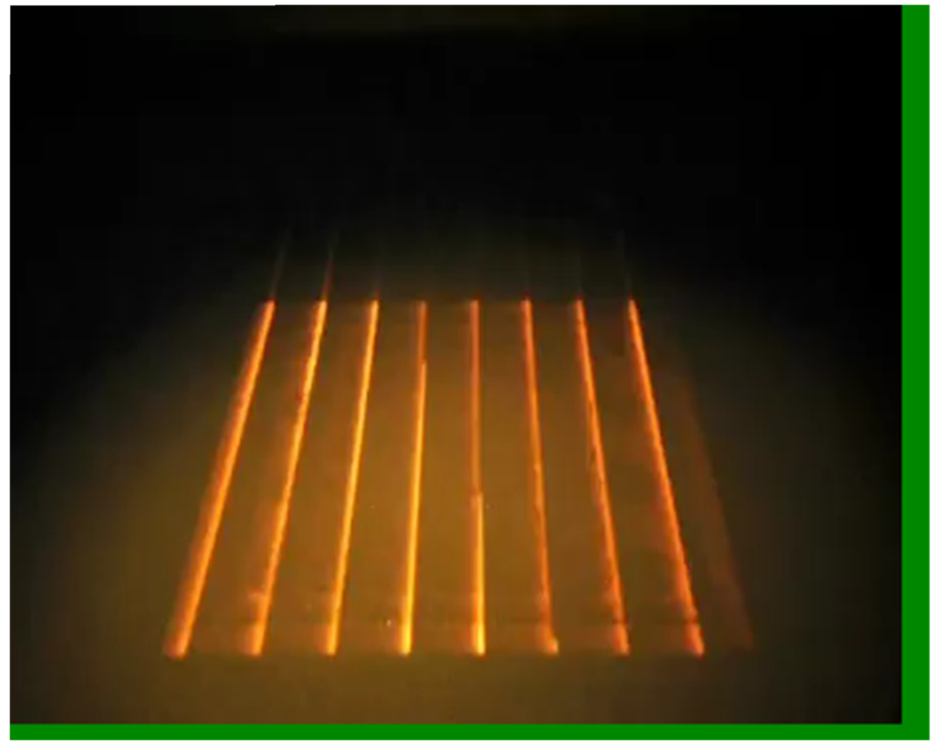
EB based Machining: The Virtue of Electrons

Mass	9.1×10^{-31} kg
Charge	-1.6×10^{-19}coulombs
Virtue of Electron=Kinetic Energy	





One can surprised that how such a lightweight particle can produce an amount of energy that can melt metal !!

So, it's not weight but its velocity which can be increased to 2/3rd speed of light.

Schultz, H., 1993. *Electron beam welding* (Vol. 93). Woodhead Publishing.

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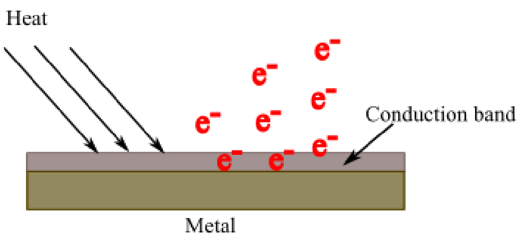
EB based machining: Highlight

Accelerating voltage	**: 50 to 200 kV**
Beam current	: 100 to 1000 µA
Electron velocity	: 1.6 x 10^8 m/s
Power density	: 6500 billion W/mm^2
Medium	: Vacuum (10^-5 to 10^-6 mm of Hg)
Workpiece material	: All materials
Depth of cut	: Up to 6.5 mm
Material removal rate	: Up to 40 mm^3 / s
Specific power consumption	: 0.5 to 50 kW

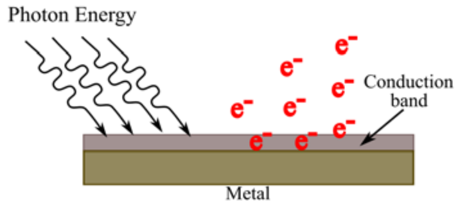
EB based Machining: Electron's Emission

To emit or produce electrons from any solid state material, minimum energy equal to Work Function also known as potential barrier needs to be given.

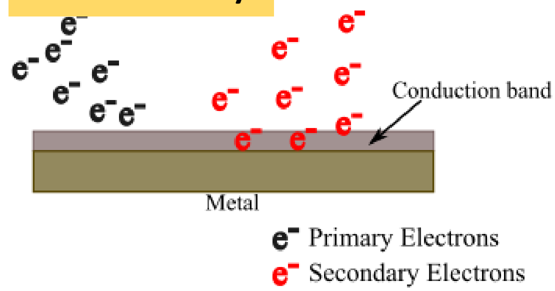
Thermionic



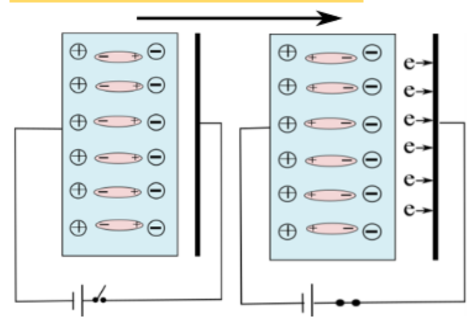
Photon



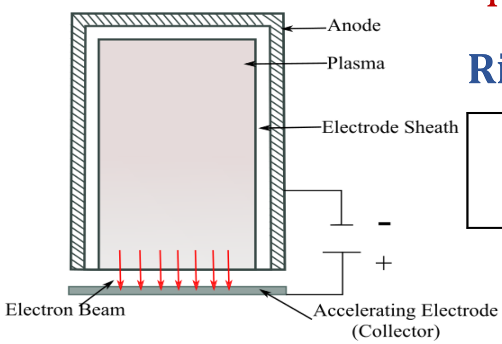
Secondary



Ferro Electric



Plasma



For metal processing such as welding, lithography, microscope, machining etc. Thermionic and Plasma Emission are popular to use.

Richardson Law for Thermionic Emiission

$J = AT^2 e^{-\frac{11600w}{T}}$	(1)

J – Current density emitted from the emitter surface (A/cm^2)

A - Constant (120.4 A/cm^2-K^2)

T -Absolute temperature of the emitter (K). (2500°C for W)

w -Work function of the emitter (4.52 eV for tungsten and 4.1 eV for tantalum)

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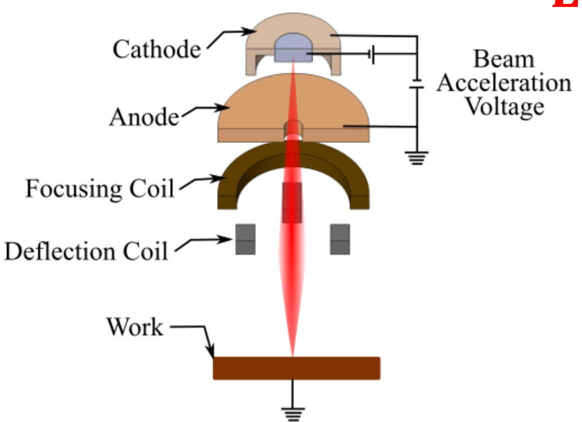
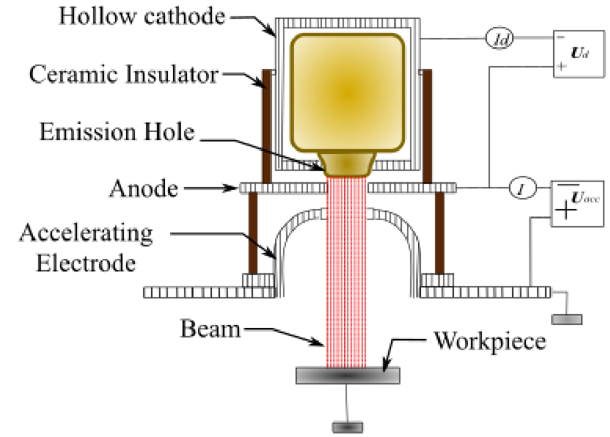
EB based Machining: Electron Beam Gun



Thermionic EB Gun

The function of the Electron Beam(EB) Gun is to produce, focus and deflect as per requirement



Plasma EB Gun

Comparison of Thermionic and Plasma gun		
Parameters	Thermionic Gun	Plasma Gun
Current density	1-10 A/cm^2	1-10^2 A/cm2
Acceleration voltage	1-150kV	1-30kV
Vacuum	$10^{-7} - 10^{-9}\ bar$	$10^{-4} - 10^{-5}\ bar$
Life	Short 50 hr	Long >100 hr
Cost	More due to high vacuum	Less
Application	Melting, heating, machining, welding	

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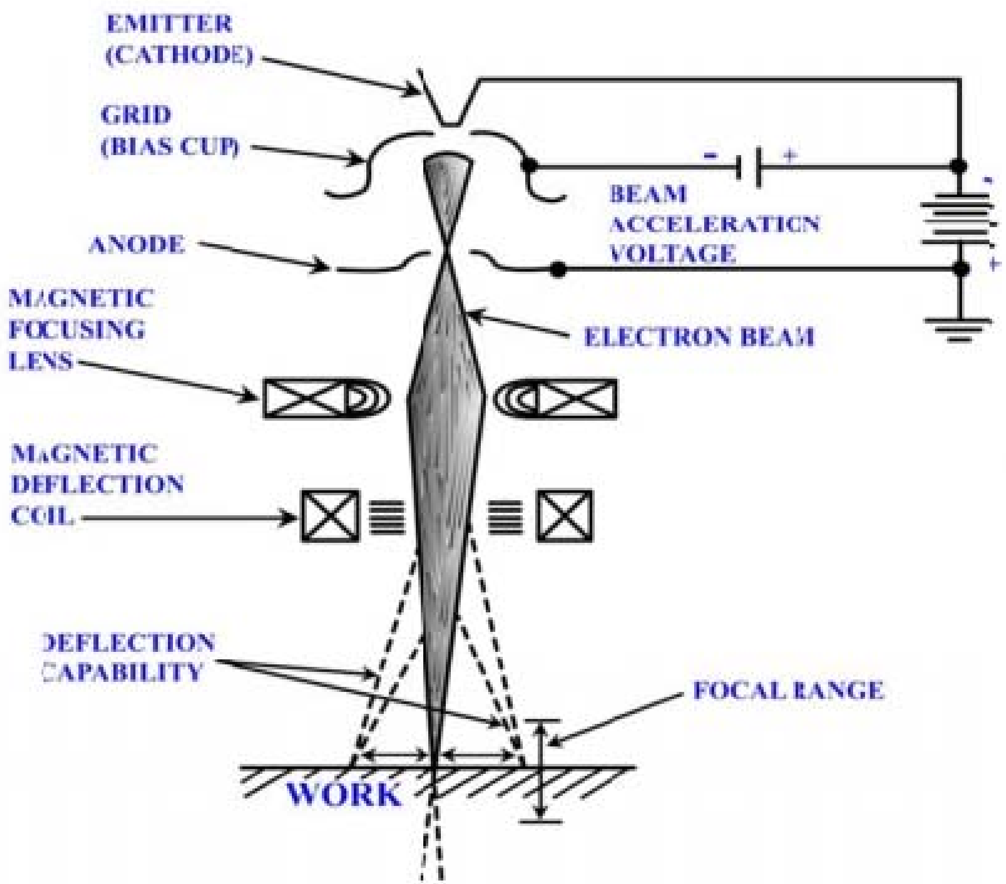
EB based Machining: Electron Beam Gun: Construction



EB based Machining: Electron Optics: Focusing

In most of the EB guns used in manufacturing, electrostatic field is used for the extraction and acceleration of the electron beam and magnetic fields for focusing, deflecting and correction. Schematic of such type pf EB gun is shown in Figure1. Components of the Lorentz force given in the equation 1 are used for the focusing. From cathode to anode focusing is done by electro-static force and from anode to required area by electro-magnetic area. In first stage focusing, magnitude of the electron's velocity increases due to electric field and in second stage, direction of the velocity changes while magnitude remains same.

$$F = q\,(\vec{E} + \vec{v} \times \vec{B}) \qquad (1)$$

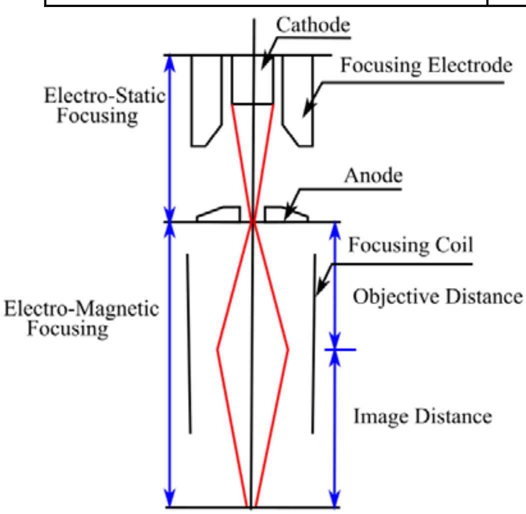


Figure 1: Focusing in Electron Beam gun

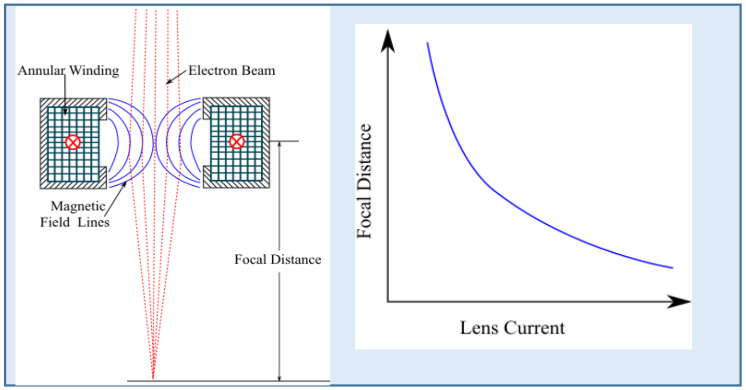
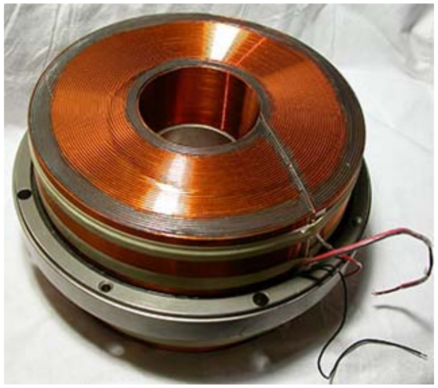


Figure 2: Focusing of EB by focusing coil



Focusing coil used for TEM

Lenses: electromagnetic lenses | MyScope. (2012, October 10). Myscope.Training.https://myscope.training/legacy/tem/background/concepts/lenses/

$$\frac{1}{f} = \frac{\pi \quad e^2}{16 m E_0} a {B_0}^2$$

E_0= Acceleration Voltage

B_0 = Magnetic field

f=focal length

a= width of focusing coil

m= mass of electrons

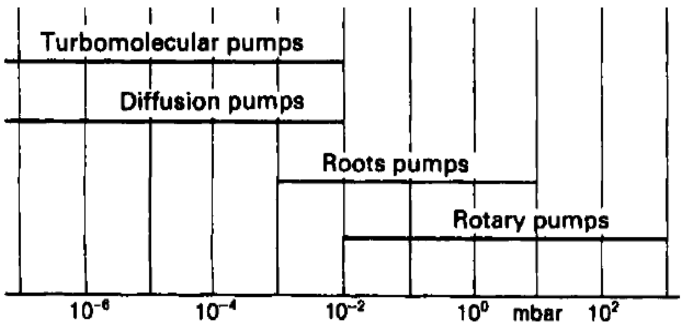
e =Charge on electrons

EB based Machining: Electron Optics: Need of Vacuum

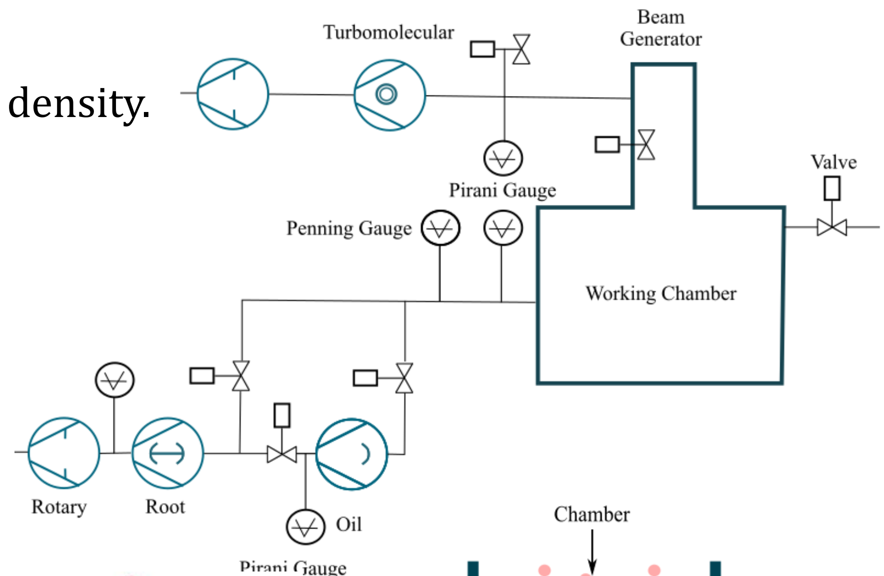
Vacuum= Removal of air particle

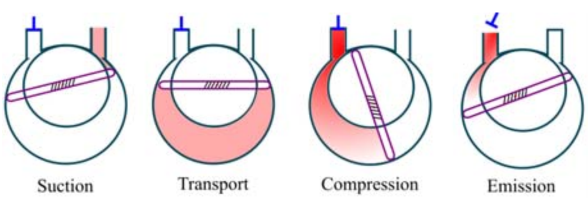
Need of Vacuum

- Electron should be focused to achieve the required power density.
- Prevent oxidation of the filament

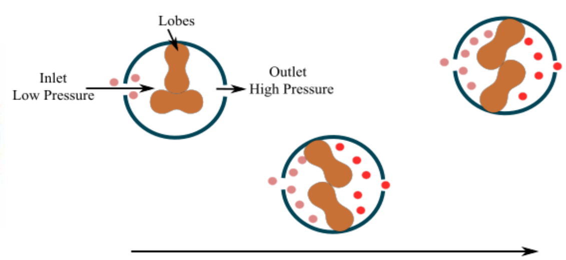


Circuit diagram

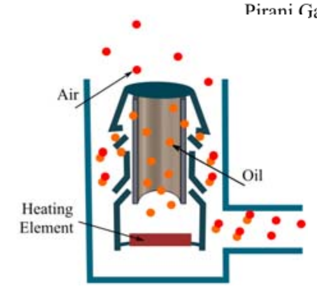




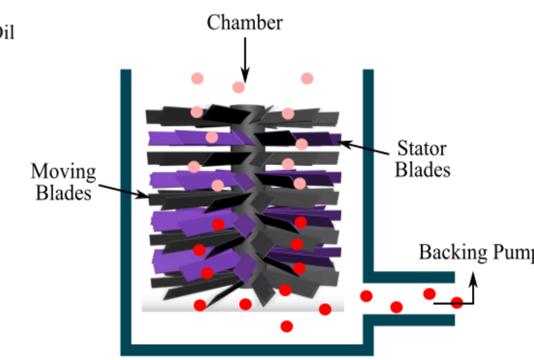
Rotary Pump



Roots Pump



Diffusion Pump



Turbomolecular

Electron Optics: Deflection

In Electron Beam gun, electrons are deflected by Electro Magnetic lenses which generate the force shown in equation 1 to move the Electron Beam.

$$F_{em} = q\,(\vec{v} \times \vec{B}) \quad (1)$$

V= total velocity of the Electrons , q= Charge on Electrons
B= Magnetic Field

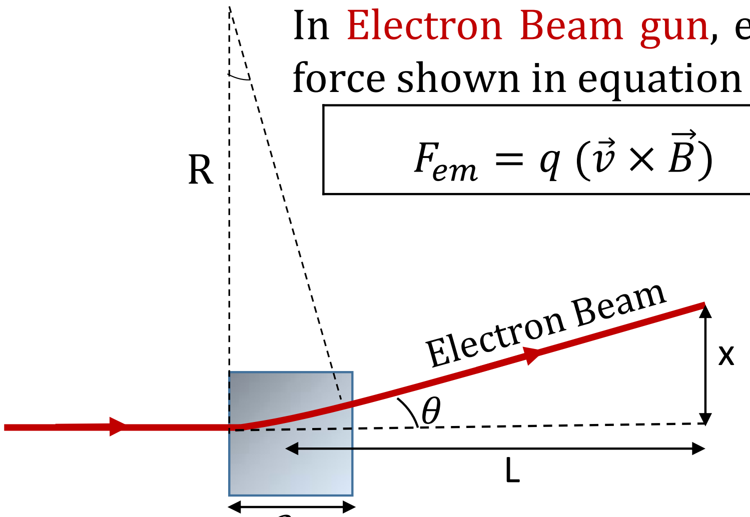


Figure 1: Deflection of the Electron Beam

Where x is deflection (m)
L is beam throw distance (m)
V acceleration voltage (V).
B is the magnetic field (Tesla)
a is the width of constant magnetic field (m)

$$\frac{mv^2}{R} = qvB,\ R = \frac{mv^2}{qvB}$$

$$\frac{1}{2}mv^2 = eV,\ \ v = \sqrt{\frac{2eV}{m}},$$

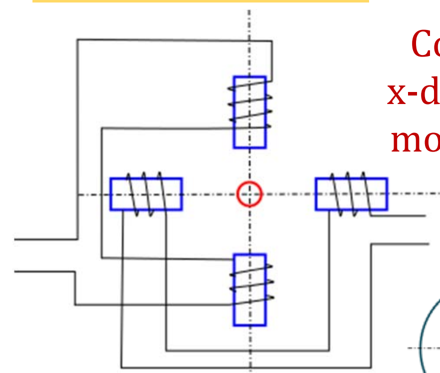
$$R = \frac{2eV}{qvB}$$

$$\tan\theta \cong \frac{a}{R} = \frac{x}{L}$$

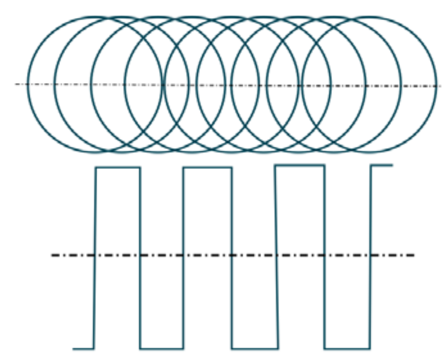
$$x = \frac{aL}{R}$$

$$x = \frac{aLqvB}{2eV}$$

Deflection coils



EB Pattern



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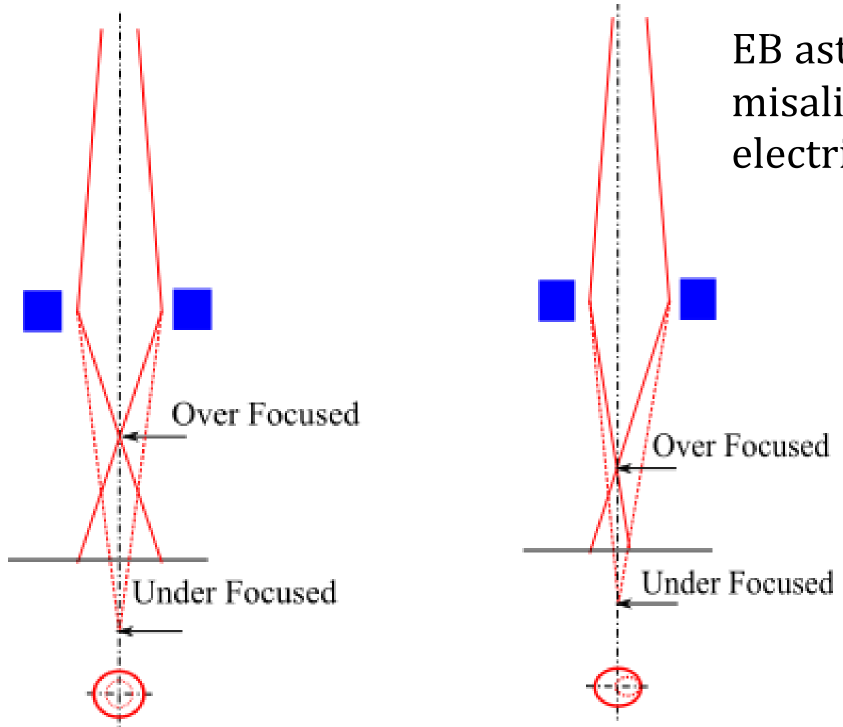
Electron Beam Gun: Correction

Stigmators are the electromagnetic coils with multipoles used to correct electron beam shape.

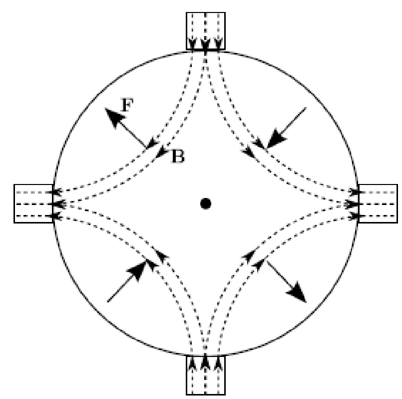
EB astigmatism occurs due to error in EB optical system such as misalignment between the electrodes or interface between electric and magnetic fields



(a) b)

Variation in diameter of the beam when beam is focused and under focused when beam is align at normal(a), beam is not aligned(b)

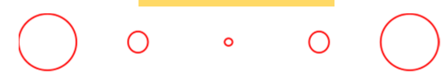
Quadrupole Stigmator



Azhirnian, A., & Svensson, D. (2017). *Modeling and analysis of aberrations in electron beam melting (EBM) systems* (Doctoral dissertation, Master's Thesis, Department of Physics, Chalmers University of Technology).

Astigmatic Aberration

Corrected



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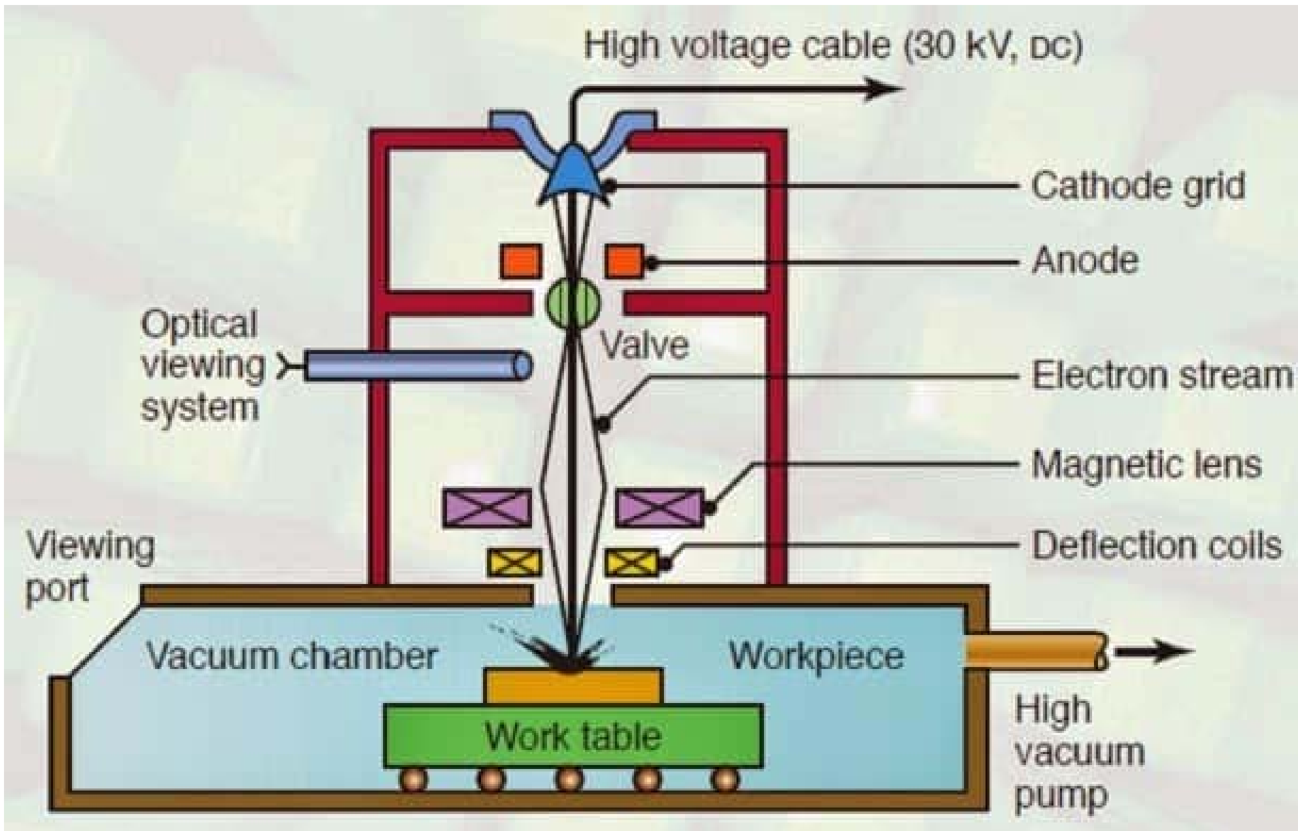
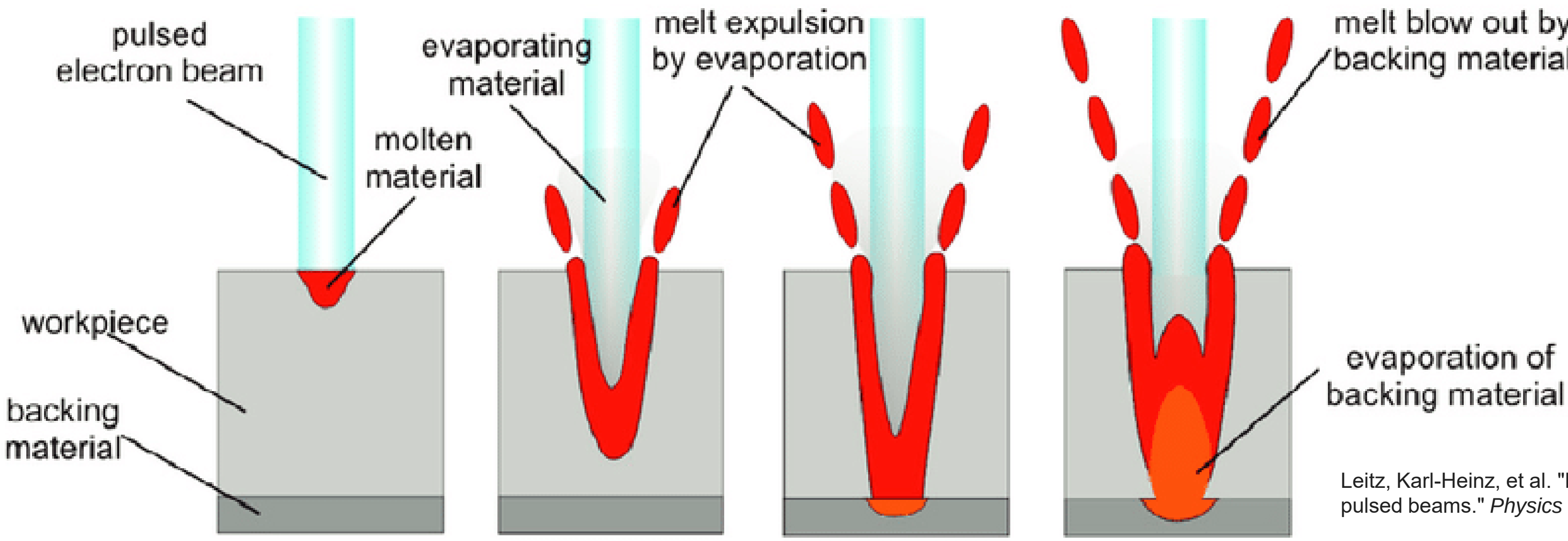
Electron Beam Gun: No Correction Coils



EB based Machining: Drilling



Leitz, Karl-Heinz, et al. "Numerical simulation of drilling with pulsed beams." *Physics Procedia* 39 (2012): 881-892.

Figure shows the principle of the electron beam drilling process. A pulsed electron beam is focused onto a workpiece leading to its heating, melting and evaporation. Ablation is based on two processes: evaporation and melt expulsion. When the drill hole fully penetrates the sheet, the electron beam hits a backing material of low evaporation threshold. The additional evaporation pressure of the vaporized backing material leads to a final blow out of the remaining melt.

EB based machining: Drilling

Typical drill hole diameters are on the scale of 0.05 up to 1 mm in material of up to 10 mm thickness, at perforation rates of 10 to 3000 holes per second.

https://www.sst-ebeam.com/en/application-areas/drilling.html

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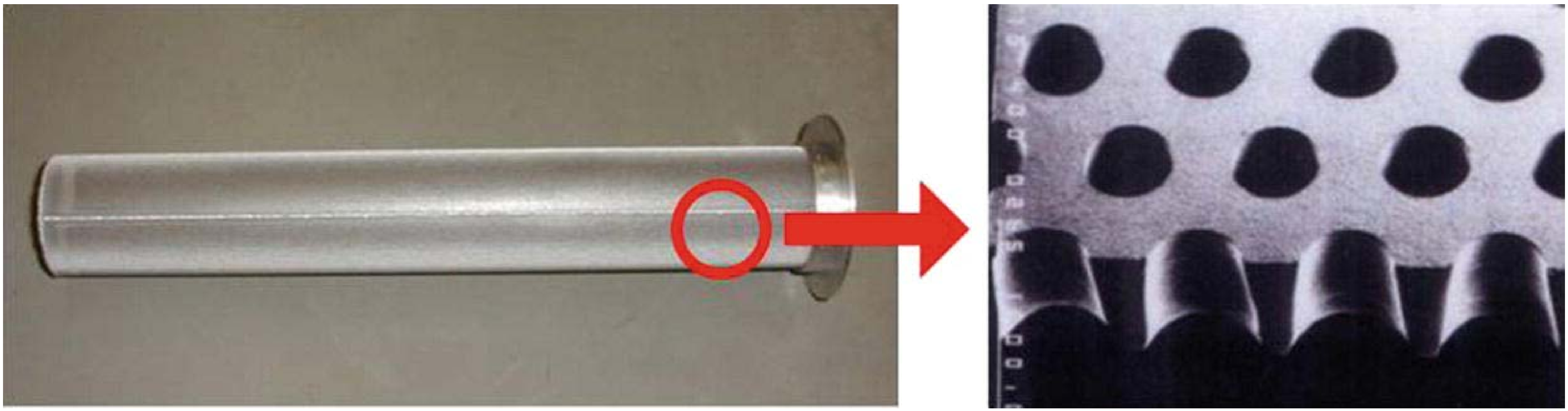
EB based machining: Drilling



https://link.springer.com/referenceworkentry/10.1007/978-3-642-20617-7_6480

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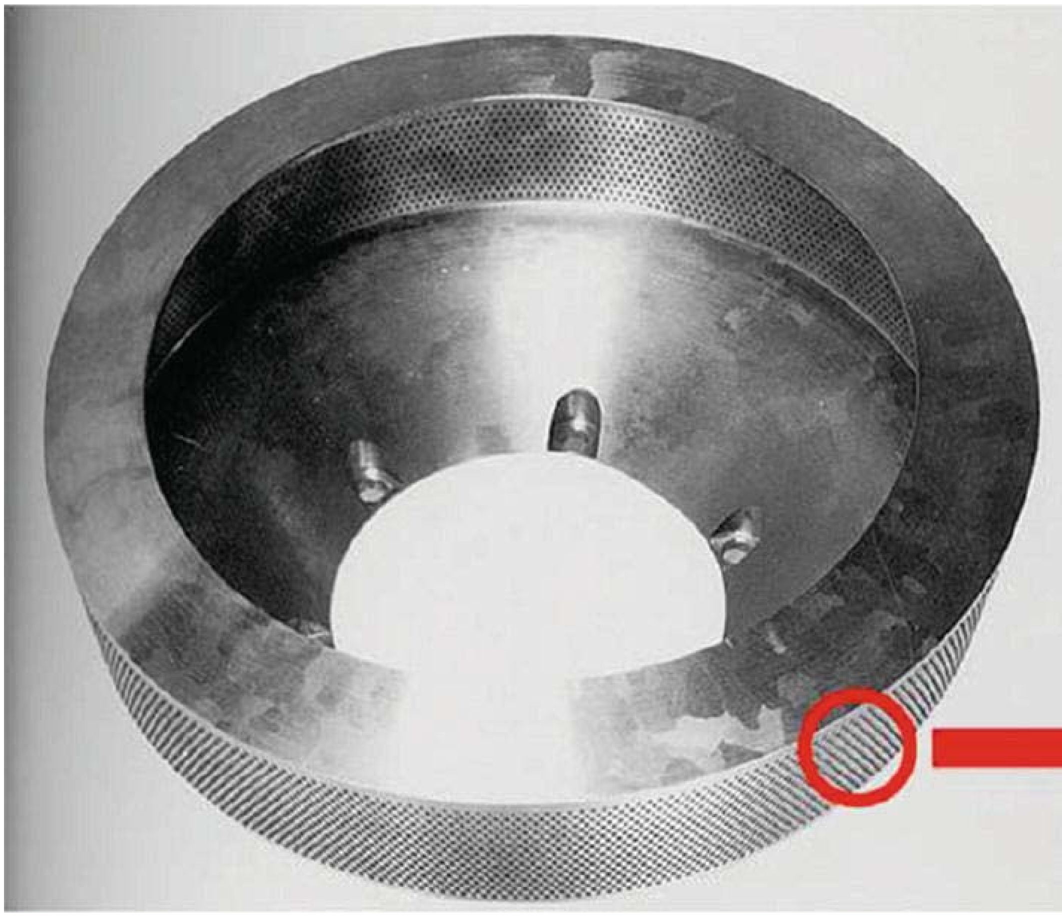
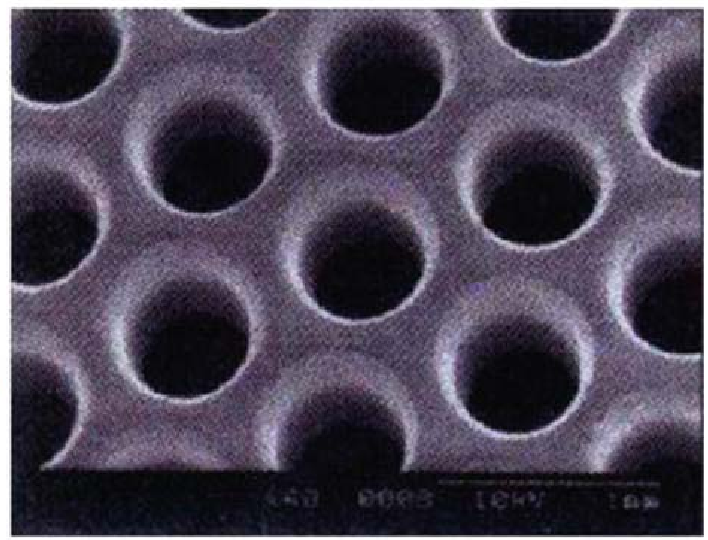
EB based machining: Drilling

https://link.springer.com/referenceworkentry/10.1007/978-3-662-53120-4_6480





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EB based machining: Drilling

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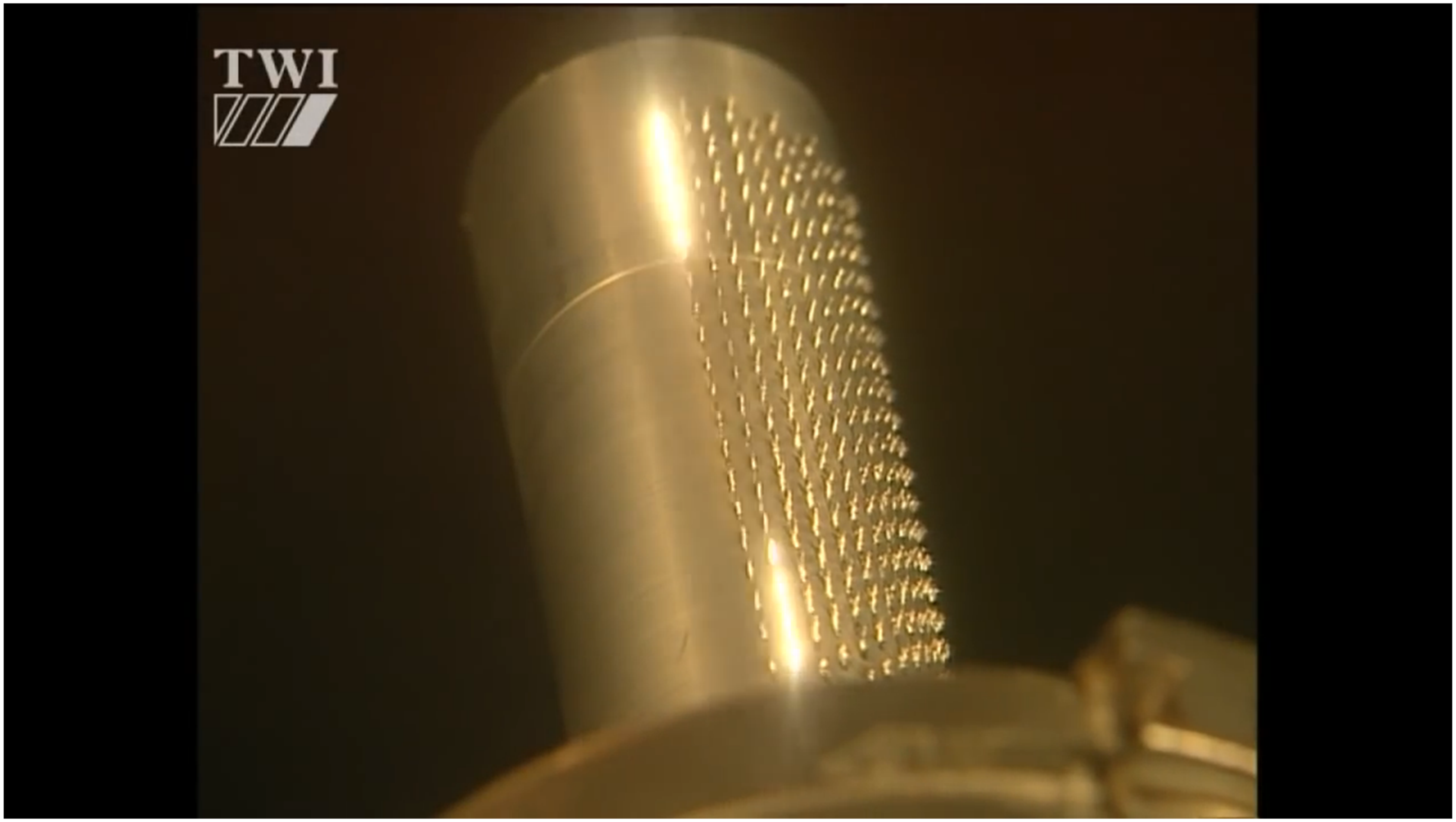
EB based machining: Drilling



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EB based machining: Advantages

1. It is an excellent process for micro finishing (milligram/ s).
2. Very small holes can be machined in any type of material to high accuracy.
3. Holes of different sizes and shapes can be machined.
4. There is no mechanical contact between the tool and the workpiece.
5. It is a quicker process. Harder materials can also be machined at a faster rate than conventional machining.
6. Electrical conductor materials can be machined
7. The physical and metallurgical damage to the workpiece is very less.
8. This process can be easily automated.
9. Extremely close tolerances are obtained.
10. Brittle and fragile materials can be machined.

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EB based machining: Disadvantages

1. The metal removal rate is very slow.
2. The cost of equipment is very high.
3. It is not suitable for large workpieces.
4. High skilled operators are required to operate this machine.
5. High specific energy consumption.
6. A little taper produced on holes.
7. Vacuum requirements limit the size of the workpiece.
8. It is applicable only for thin materials.
9. At the spot where the electron beam strikes the material, a small amount of recasting and metal splash can occur on the surface. It has to be removed afterward by abrasive cleaning.

Thank You

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Research Int.: Manufacturing Automation, 3D Printing, CAD/CAM

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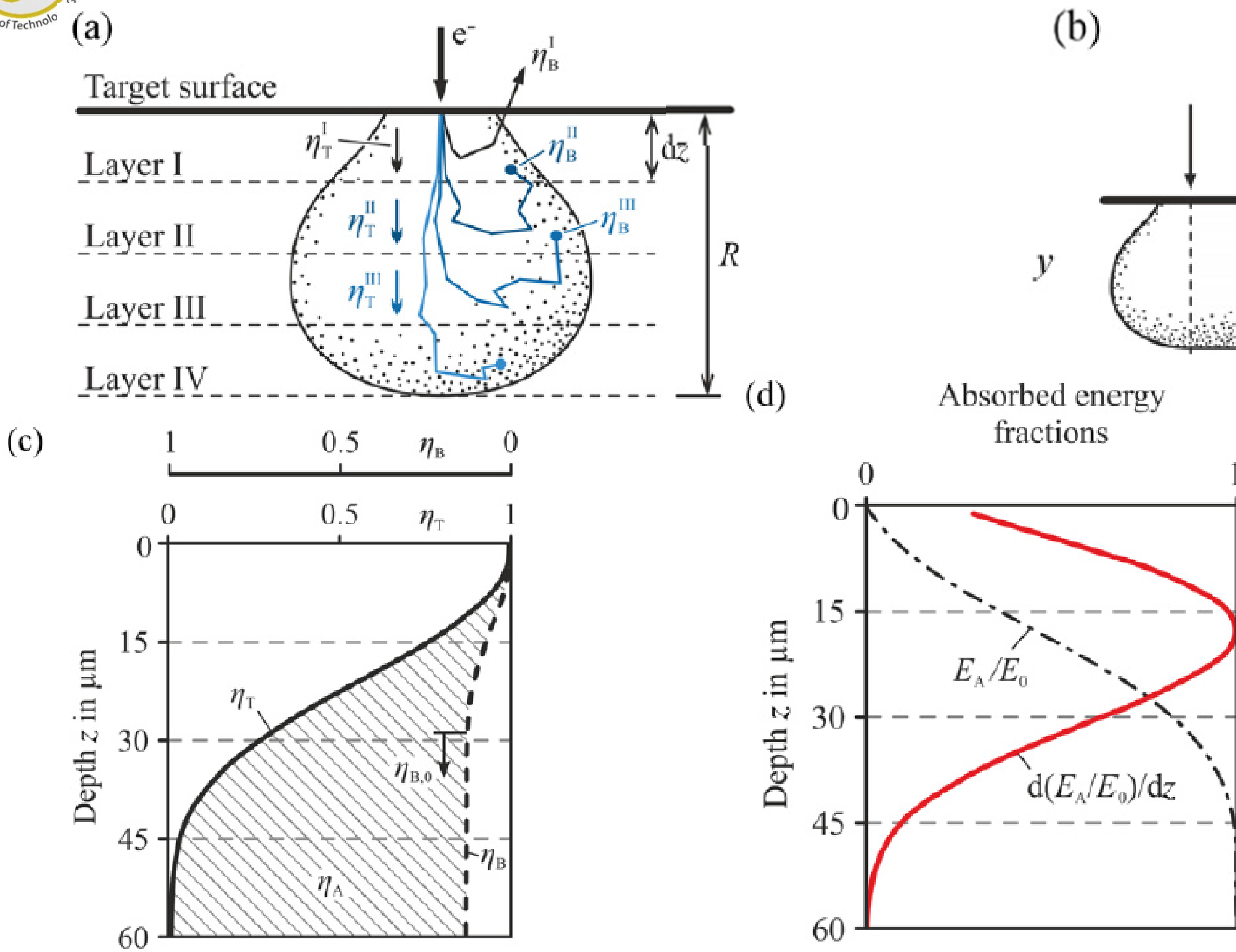

Penetration depth mainly depends on Acceleration Voltage and density of the material

$$\eta_a + \eta_b + \eta_t = 1$$

Klassen, A., Bauereiß, A., & Körner, C. (2014). Modelling of electron beam absorption in complex geometries. Journal of Physics D: Applied Physics, 47(6), 065307.