ME338 – Manufacturing Process II
Lecture 13 : EBM/LBM/Other NTM

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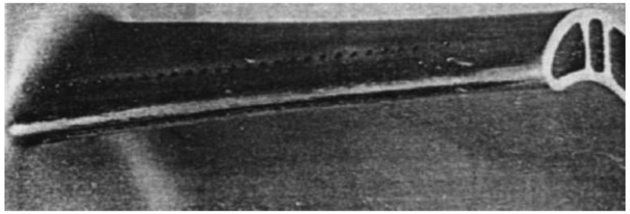
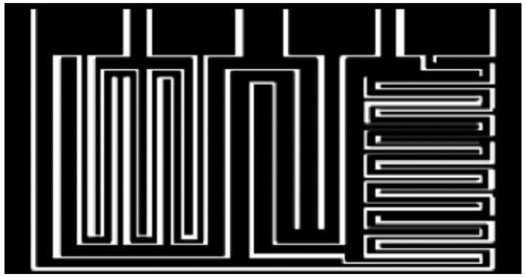
Few slides have been taken from Prof. Marla and Prof. Rakesh Mote presentations

Applications of EBM



Electron beam–drilled holes in superalloy turbine blade

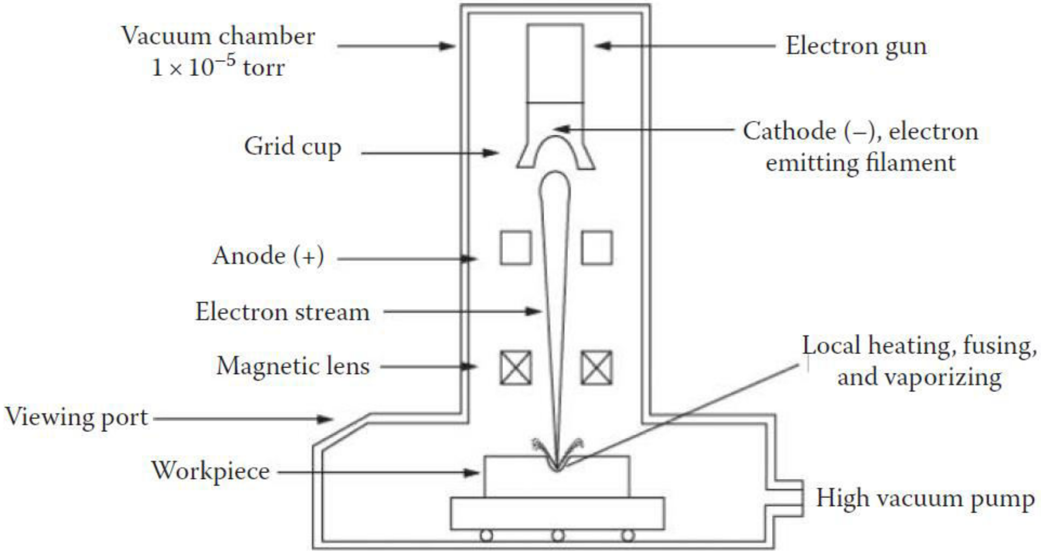


Hybrid circuit engraved with 40 μm traces at speed >5 m/s.

Electron Beam Machining (EBM)

- EBM has been used in nuclear and aerospace welding industries since the early 1960s.
- Drilling small holes, cutting, engraving, and heat treatment are a set of modern applications used in semiconductor manufacturing as well as micromachining areas.
- Used extensively in the preparation of photomasks required in electronics applications.
- EBM is a thermal based process, where high speed electrons impinges on the workpiece.
  - Transfer of kinetic energy into thermal energy
  - Very high electron velocity (200,000 Km/s)can be obtained by using higher voltage (~150 kV), resulting into power density ~10^9 W/mm^2.
  - Low pressure (10^{-5} mm Hg) working environment is needed to avoid unnecessary collusion between electrons and air

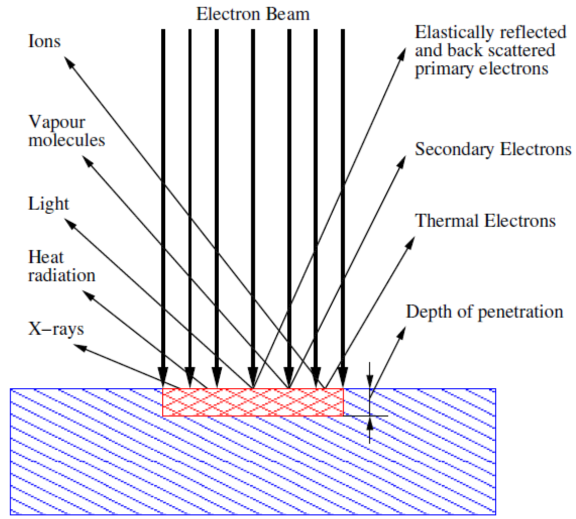
Electron Beam Machining: Schematic



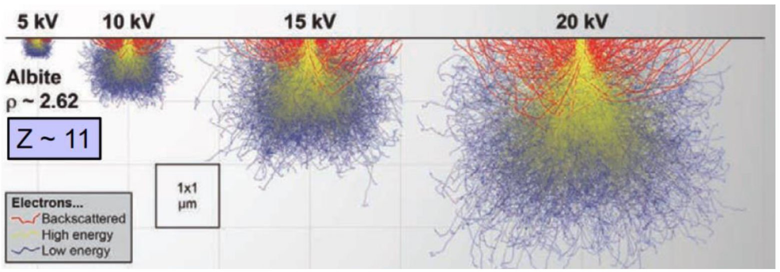
Electron Beam Machining: How it works

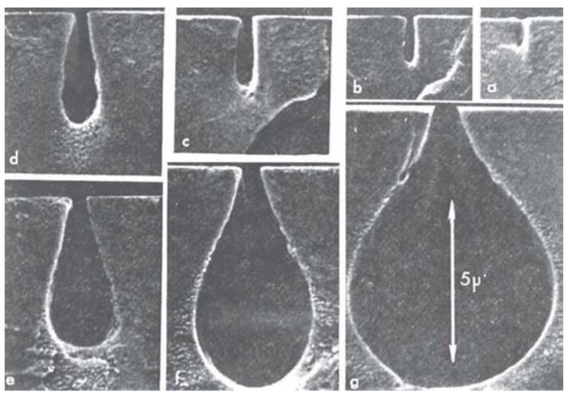
- The tungsten filament (cathode) is heated to about 2000°C–2500°C to emit electrons.
  - Electrons are emitted by thermionic emission
  - Current density J due to thermionic emission is given by Richardson-Dushman equation
  - $J = AT^2 e^{-\frac{We}{k_b T}}$
  - W : Work function, e : electron charge, Kb: boltzmann constant, T: temperature
- The concave shape of the cathode grid concentrates the stream through the anode.
- A potential difference of 150 kV is applied between cathode and anode, which is used to accelerates the electrons.
- After acceleration, electrons focused by the field travel through a hole in the anode
- The electron beam is then refocused by a magnetic or electronic lens system so that the beam is directed under control toward the workpiece.
- The kinetic energy of the electrons is then rapidly transmitted into heat
  - Rapid increase in the temperature of the workpiece, > boiling point, thus causing material removal by evaporation.
  - The melted liquid is rapidly ejected and vaporized, causing a material removal rate within the range of 10 mm^3/min.

Electrons interaction with workpiece material



Simulations of Electron Beam Interaction with a Solid

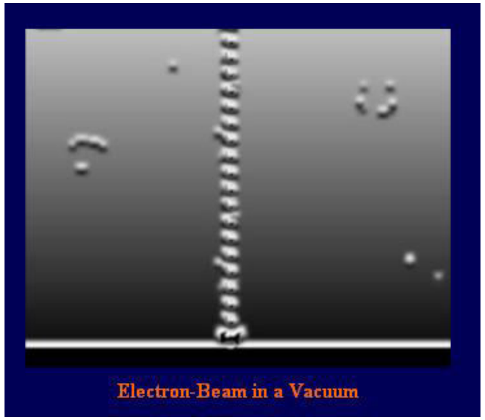


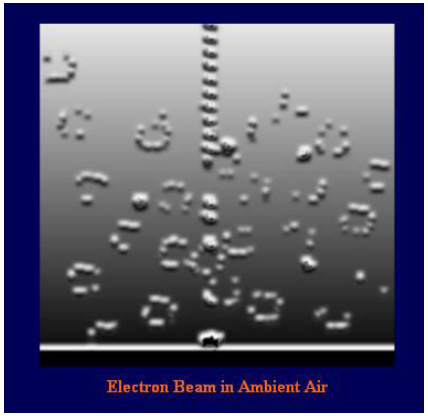


Material removal in EBM

- When electrons impinge a solid surface, it causes heating in a very narrow depth. For metals, the depth of interaction is approximately given by:
- $\delta = A\frac{V^2}{\rho}$
  - δ is interaction depth (in m),
  - V is the applied voltage (in Volts),
  - ρ is the density of the material (in kg/m^3) and
  - A is a constant
- Electrons emitted at the cathode are accelerated under the applied electric potential leading to gain in their kinetic energies.
  - The electron velocity () can be found: $\frac{1}{2}mV_e^2 = eV \approx 5.93 \times 10^5\sqrt{V}$
- The minimum required power (P_{min}) to cause vaporization of the workpiece material can be calculated by equating the energy balance:
  - $\eta P_{min} t_{on} = mc_p(\theta_m - \theta_0) + \Delta H_l + \Delta H_v$
  - $m = \frac{\pi}{4} d_w^2 \delta\rho$

Why low-pressure environment is needed





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

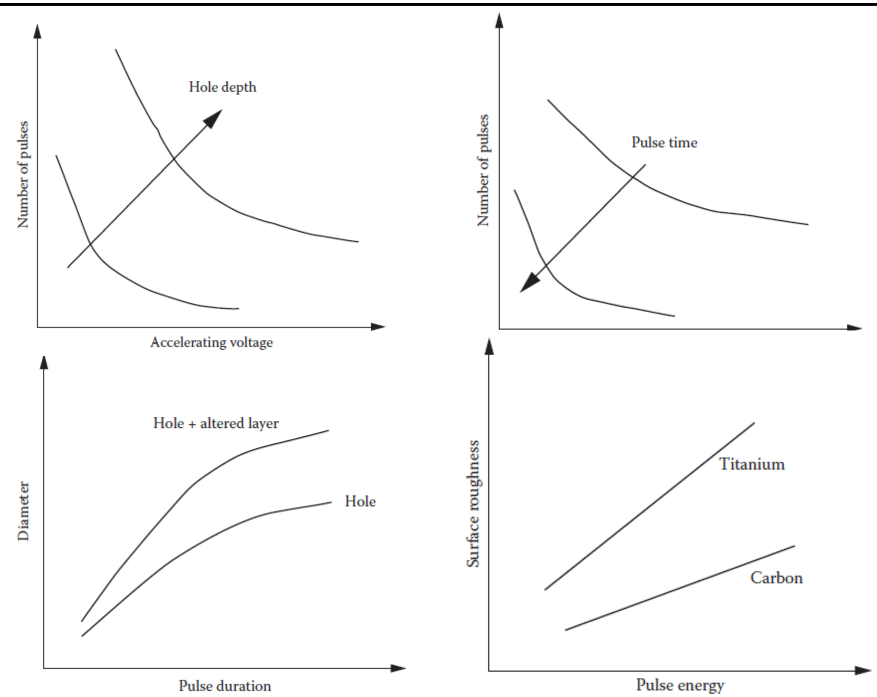
- Mechanics of material removal – melting, vaporization
- Medium – vacuum
- Tool – beam of electrons moving at very high velocity
- Maximum MRR = 10 mm3/min
- Specific power consumption = 450 W/mm3/min
- Critical parameters – accelerating voltage, beam diameter, work speed, melting temperature
- Materials 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

EBM Process Parameters and Capabilities

EBM Parameter	Level
Acceleration voltage	50–60 kV
Beam current	100–100 μA
Beam power	0.5–50 kW
Pulse time	4–64,000 μs
Pulse frequency	0.1–16,000 Hz
Vacuum	0.01–0.0001 mm mercury
Spot size	0.013–0.025 mm
Deflection range	6.4 mm^2
Beam intensity	1.55×10^5 to 1.55×10^9 W/cm^2
Depth of cut	Up to 6.4 mm
Narrowest cut	0.025 mm in 0.025 mm thick metal
Hole range	0.025 mm in 0.02 mm thick metal
Hole taper	1.0 mm in 5 mm thick metal
Hole angle to surface	1^0–2^0 typical 20^0–90^0
Removal rate	40 mm^3/s^{-1}
Penetration rate	0.25 mm/s^{-1}
Perforation rate	Up to 5,000 $holes/s^{-1}$
Tolerance	±10% depth of cut
Surface roughness	1 μm R_a

Source: El-Hofy, H., Advanced Machining Processes, Non-Traditional and Hybrid Processes, McGraw-Hill Book

Effect of critical process parameters

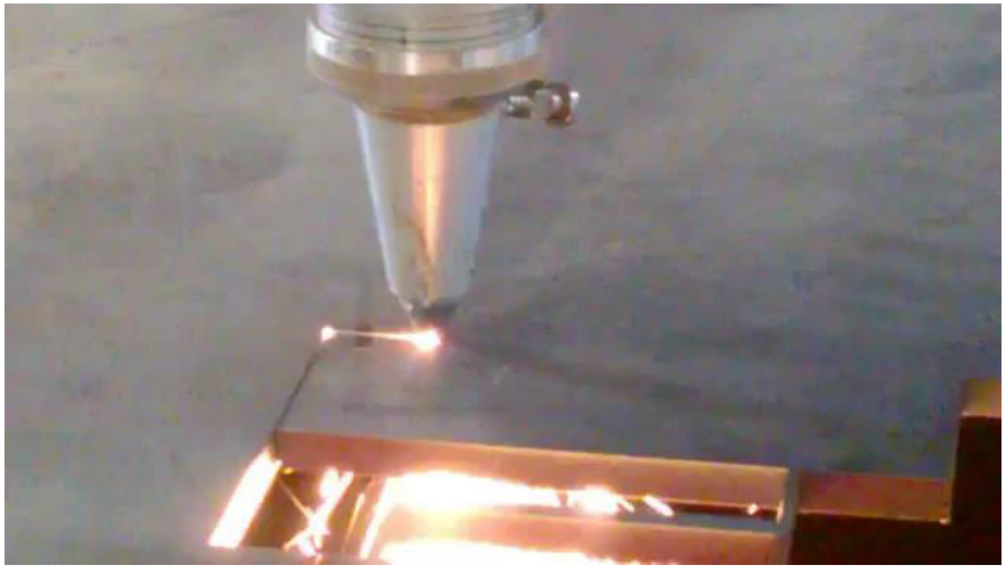


Pros/Cons of EBM

- Advantages:
  - Can create smaller, Higher Aspect ratio holes at faster rate in any material irrespective of their properties
  - Provides no limitation to workpiece hardness, ductility, and surface Reflectivity
  - Avoids mechanical distortion to the workpiece because there is no contact
  - Achieves high accuracy and repeatability of ±0.1 mm for position of holes and ±5% for the hole diameter
  - Smaller HAZ
- *Disadvantages*
  - High capital equipment cost and maintenance
  - Requirement of vacuum >> limited size of sample
  - The presence of a thin recast layer in deep holes

Laser beam machining: rust removal

Laser beam machining: slot cutting

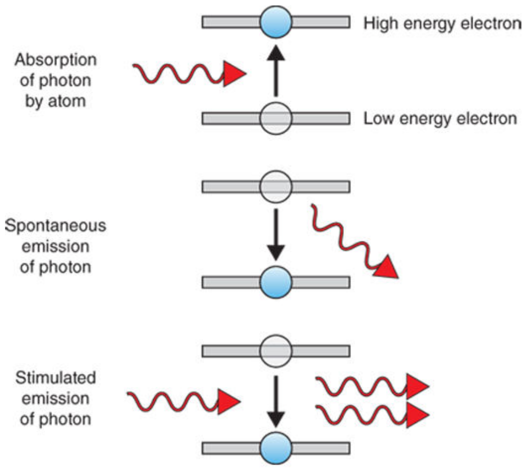


Laser beam machining (LBM)

- Laser : A device that emits light through a process of optical amplification based on stimulated emission of electromagnetic radiation.
  - L - Light
  - A - Amplification
  - S - Stimulated
  - E - Emission
  - R – Radiation

Laser : Stimulated Emission

- The concept of stimulated emission was first postulated by Einstein in 1916
- Stimulated emission is the process by which an incoming photon of a specific frequency can interact with an excited atomic electron (or other excited molecular state), causing it to drop to a lower energy level.



Source: P. Riordan-Eva, J. J. Augsburger: Vaughan & Asbury's General Ophthalmology, Nineteenth Edition
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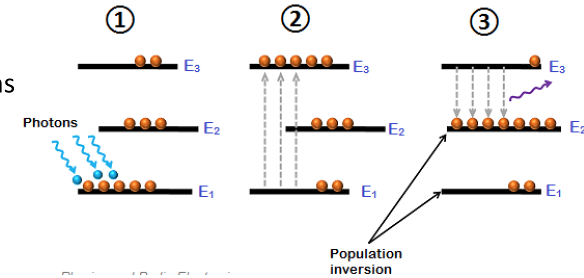
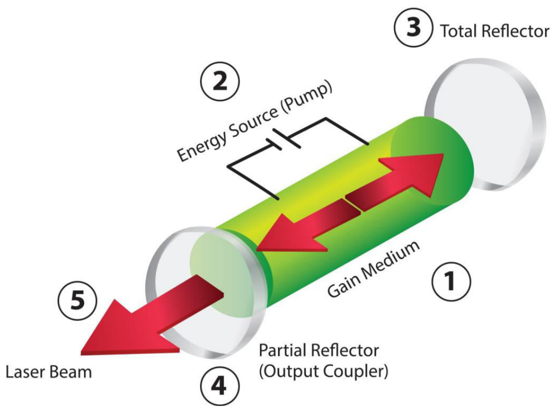
Laser : Population Inversion

- Under normal conditions, more electrons are in a lower energy state than in a higher energy state.
- Population inversion is a process of achieving more electrons in the higher energy state than the lower energy state.
  - In order to achieve population inversion, we need to supply energy to the laser medium.
  - The process of supplying energy to the laser medium is called pumping.
- Pump sources
  - Optical pumping
  - Electric discharge
  - Inelastic atom-atom collisions
  - Thermal pumping
  - Chemical reactions



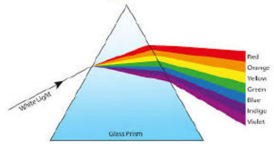
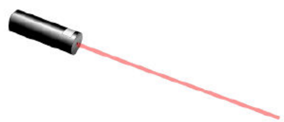
Laser : Operating Principle



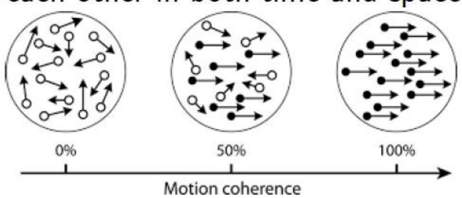
- Gain medium capable of sustaining stimulated emission
- Light is amplified in the gain medium
- Light bounces back and forth between the mirrors, passing through the gain medium and being amplified each time

Properties of Laser

- Monochromatic: Laser light is concentrated in a narrow range of wavelengths

- Coherent: All the photons bear a constant phase relationship with each other in both time and space



- Directionality: Laser light is usually low in divergence
- High irradiance: has very high intensities from 10^9 W/m^2

Laser types

Solid–state	Dye	Gas	Excimer	Chemical
–Ruby	– Rhodamine	– CO2	– KrF	– Oxygen–Iodine
– Nd:YAG	– Cuomarin	– He–Ne	– XeF	– Gas phase Iodine
– Fiber	– Tetracene	– Ar		
– Semiconductor				

- Continuous lasers
- Pulsed Lasers: microsecond - nanosecond - picosecond - femtosecond

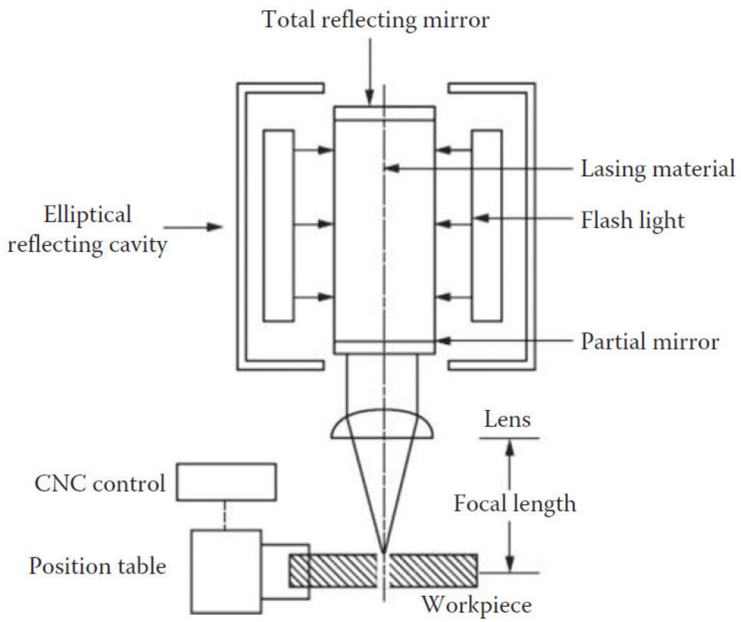
Femtosecond laser are required for machining hard materials such as silicon/quartz

Laser beam machining : Types of Lasers

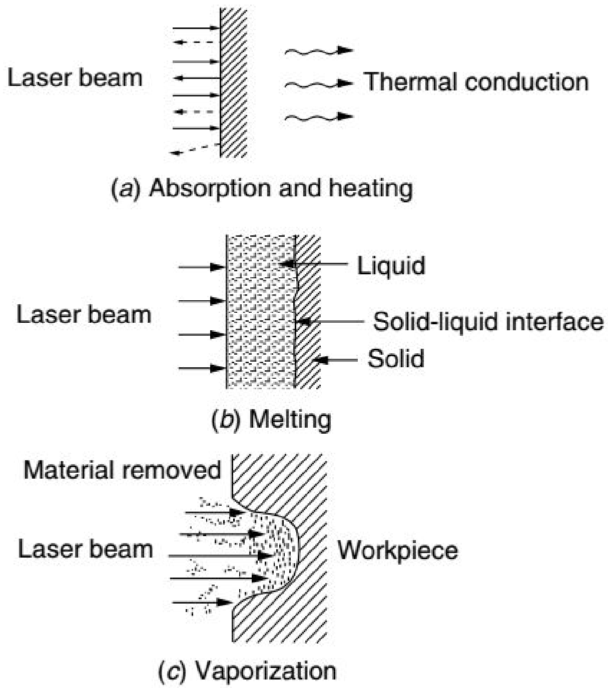
Different Types of Lasers

Laser Type		Wavelength (nm)	Typical Performance
Solid	Ruby	694	Pulsed, 5 W
	Nd-YAG	1064	Pulsed, cw, 1–800 W
	Nd-glass	1064	Pulsed, cw, 2 mW
Semiconductor	GaAs	800–900	Pulsed, cw, 2–10 mW
Molecular	CO_2	10.6 µm	Pulsed, cw, (<15 kW)
Ion	Ar^+	330–530	Pulsed, cw, 1 W to 5 kW
	Excimer	200–500	Pulsed
Neutral gas	He-Ne	633	cw, 20 mW

Laser beam machining

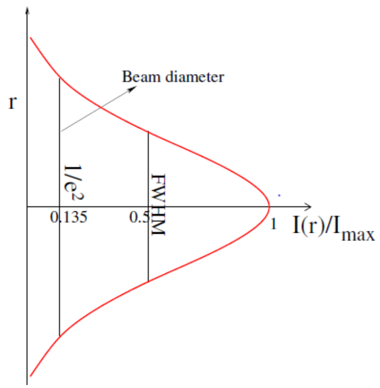


LBM : material removal mechanism



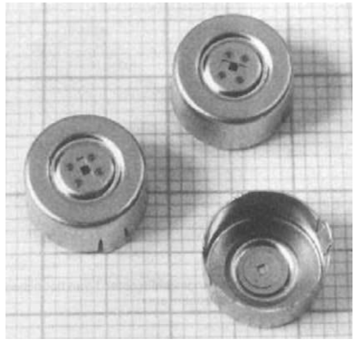
Laser beam: Diameter, Intensity and Power

- Since beams typically do not have sharp edges, the diameter can be defined in many different ways
- The most commonly accepted is the $1/e^2$ beam diameter (e = 2.718).
- It is measured as the distance between two points on the beam profile that have intensity equal to $1/e^2$ (0.135) of the peak value
- Relation between total power (P_0) and intensity I_0
- $I_o = \frac{2P_o}{\pi\omega^2}$
- $I(r) = I_o e^{-\frac{2r^2}{\omega^2}}$



LBM: Applications

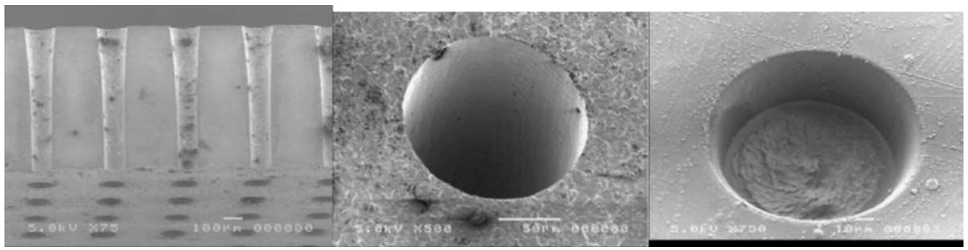
- Material Removal : Drilling, Trepanning, cutting
- Material Shaping: Scribing
- Welding
- Thermo kinetic Changes : Heat treatments



Laser welded parts for a TV electron gun (Philips CFT).

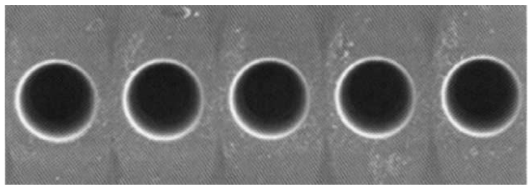
Laser welding of steel (top) on aluminium

LBM: Applications in machining



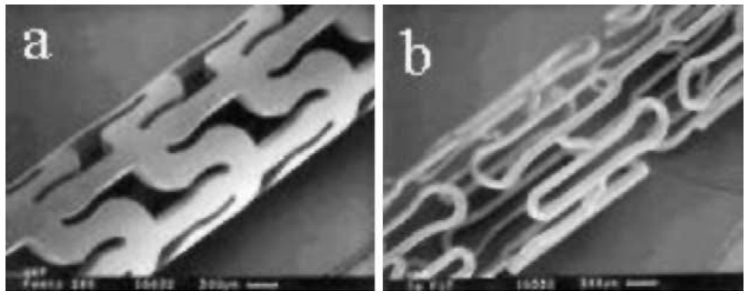
Hundred-micrometer holes for medical filters, middle close up of one hole, right blind hole.

Partial (left) and fully cleaned fine arts, Art-Innovation, NL

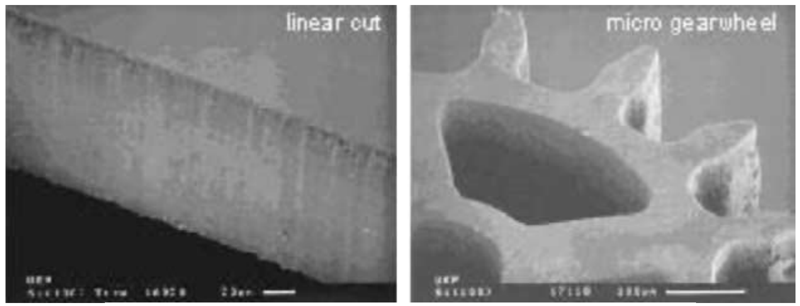


Array of ink jet nozzles drilled in 50 µm thick polyimide

Applications of LBM in medical



Prototypes of stents made of: (a) bio-resorbable polymer and (b) tantalum.

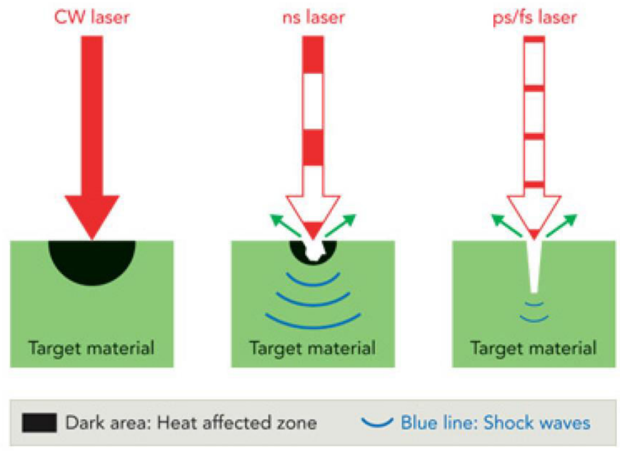


Examples of silicon cutting by Femtosecond laser

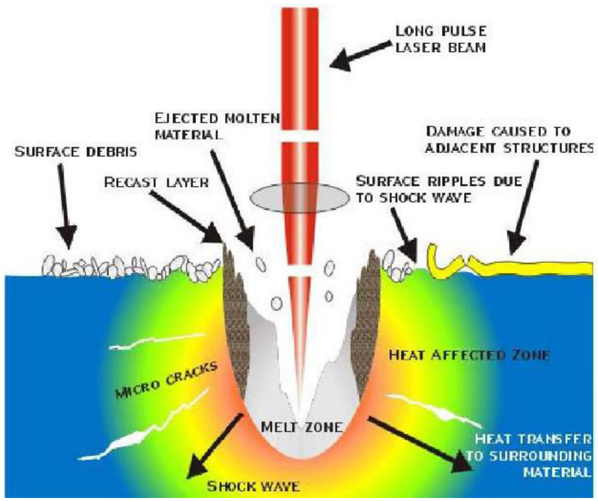
LBM : Applications

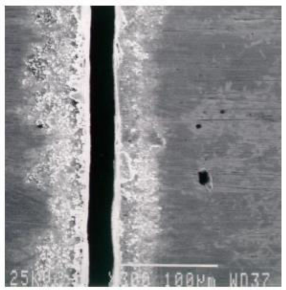
Laser	Applications	Material
Micro-electronics packaging		
Excimer	Via drilling and interconnect drilling	Plastics, ceramics, silicon
Lamp-pumped solid-state	Via drilling and interconnect drilling	Plastics, metal, ceramics, silicon
Diode-pumped solid-state	High volume via drilling, tuning quartz oscillators	Plastics, metal, inorganic
CO_2 sealed or TEA	Excising and scribing of circuit devices, large panel via drilling	Ceramics, plastics
Semiconductor manufacturing		
Excimer	UV-lithography IC repair, thin films, wafer cleaning	Resist, plastics, metals, oxides silicon
Solid-state	IC repair, thin films, bulk machining resistor and capacitor trimming	Plastics, silicon, metals, oxides silicon, thick film
CO_2 or TEA	Excising, trimming	Silicon
Data-storage devices		
Excimer	Wire stripping air bearings, heads micro via drilling	Plastics, glass silicon ceramics plastics
Diode-pumped solid-state	Disk texturing servo etching micro via drilling	Metal, ceramics metals, plastic
CO_2 or TEA	Wire stripping	Plastics
Medical devices		
Excimer	Drilling catheters balloons, angioplasty devices. Micro-orifice drilling	Plastics, metals ceramics, inorganics
Solid-state	Stents, diagnostic tools	Metals
CO_2 or TEA	Orifice drilling	Plastics
Communication and computer peripherals		
Excimer	Cellular phone, fiber gratings, flat panel annealing, ink jet heads	Plastics, silicon, glass, metals, inorganics
Solid-state	Via interconnect coating removal tape devices	Plastics, metals, oxides, ceramics
CO_2 or TEA	Optical circuits	Glass, silicon

Effect of pulse durations



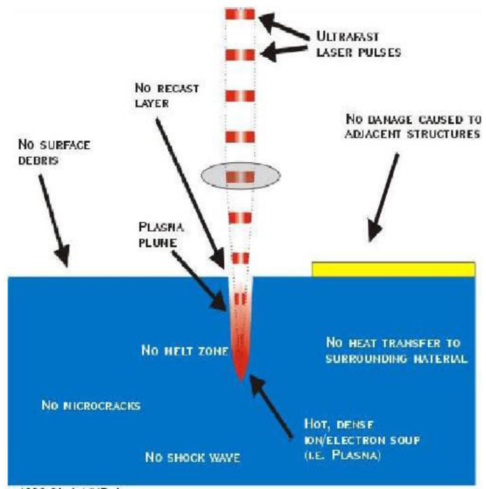
Long Pulsed Laser

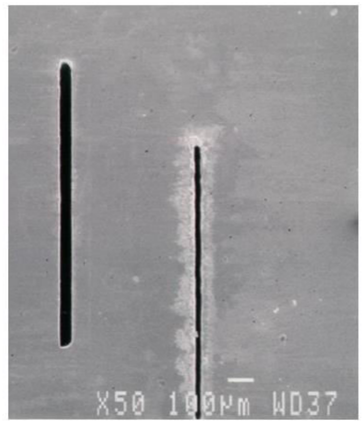




- The pulse duration is 8 ns and the energy 0.5 mJ. Example of a 25 µm channel machined in 1 mm thick INVAR with a nanosecond laser.
- Recast layer, heat affected zone, more melting

Short or ultrashort pulse Laser



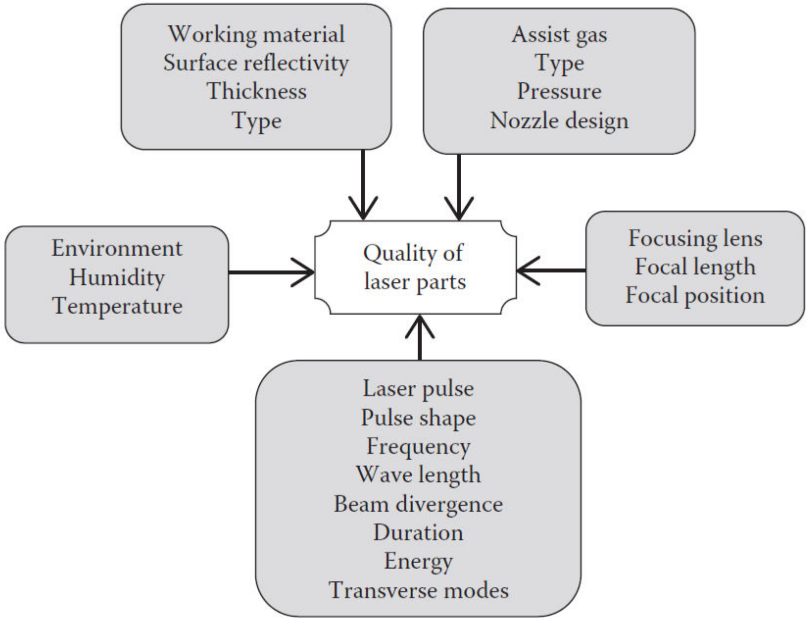


- Less surface damage and recast layer
- Less melting, instant vaporization, deep hole machining

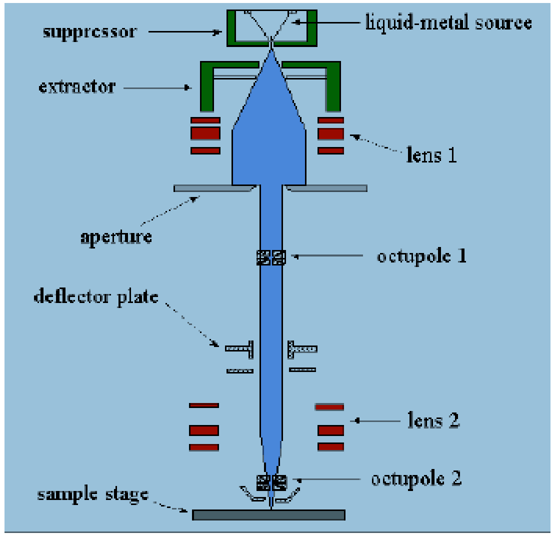
Advantages/disadvantages of LBM

- Advantages:
  - Tool wear and breakage are not encountered.
  - Holes are located accurately by using optical laser system for alignment.
  - Very small holes of large aspect ratio are produced.
  - A wide variety of hard and difficult-to-machine materials are tackled.
  - Machining is extremely rapid and the setup times are economical.
  - Holes can be drilled at difficult entrance angles (108 to the surface).
  - Due to its flexibility, the process can be automated easily.
  - The operating cost is low.
- Limitations
  - The equipment cost is high.
  - Tapers are normally encountered in the direct drilling of holes.
  - A blind hole of precise depth is difficult to achieve with a laser beam.
  - Adherent material, which is found normally at the exit holes, needs to be removed.

Critical parameters in LBM

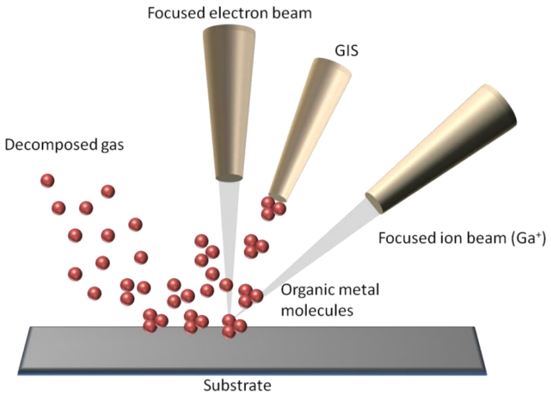


Focused Ion Beam Machining

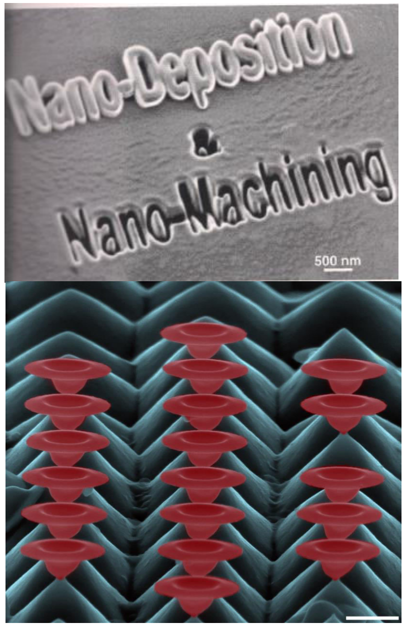


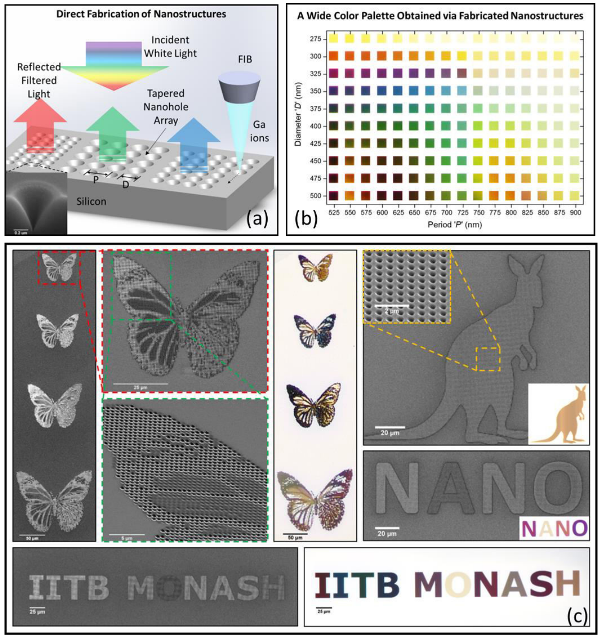
Focused Ion beam machining (FIB)

- 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



Applications of FIB*





*Prof. Rakesh Mote research work

FIB 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