Non-Traditional Manufacturing Processes (NTMP)

Lecture 3 -5: Laser Beam Machining

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Classification of Non-Traditional Manufacturing Processes (NTMP)

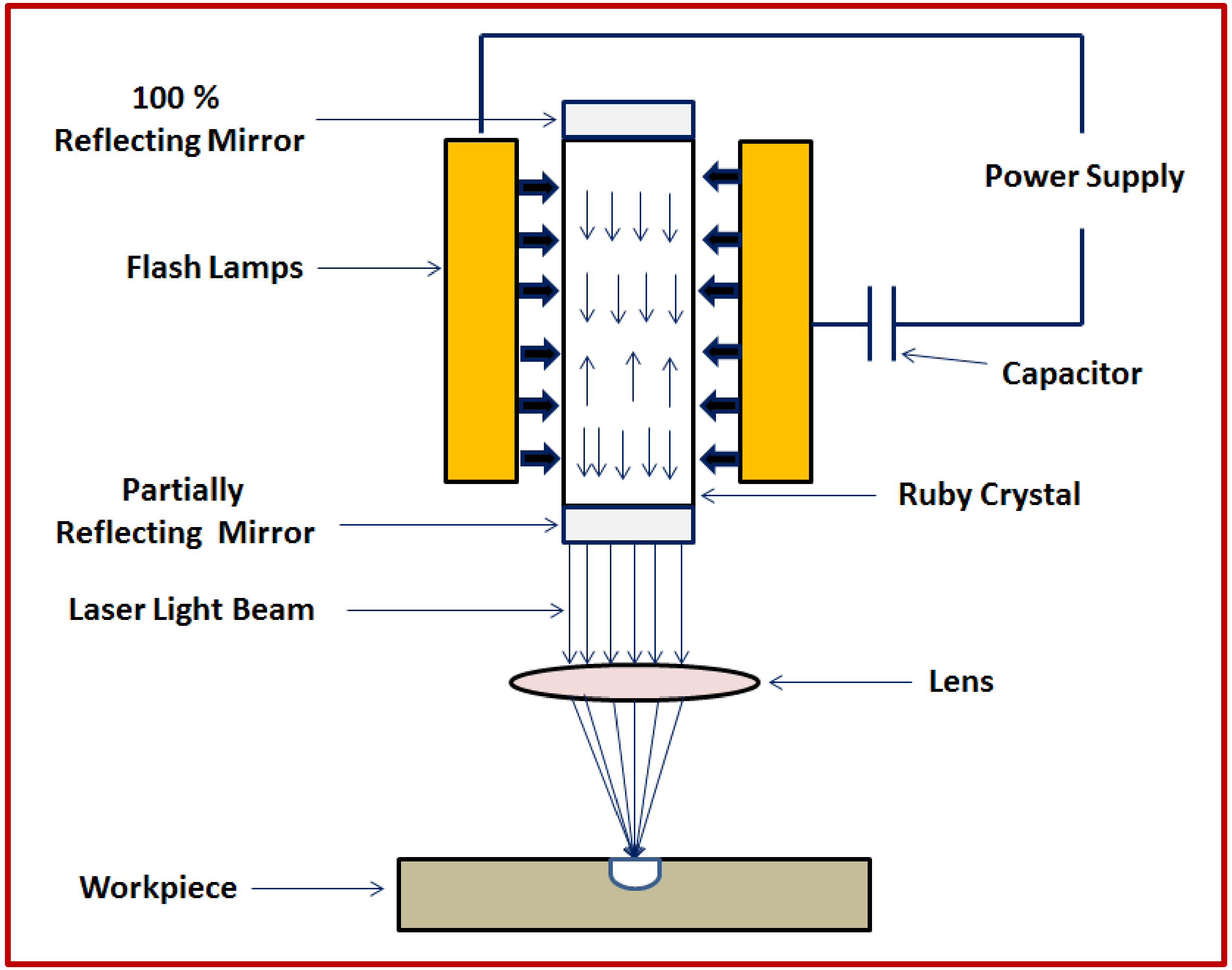
Energy type	Mechanics of material removal	Energy source	Process
Thermal	Fusion and vaporization	Light radiation	Laser beam machining (LBM)
		High speed electrons	Electron beam machining (EBM)
		Ionized substance	Plasma arc machining (PAM)
Kinetic energy	Atom by atom knocking	Ionized substance	Ion beam machining (IBM)
Mechanical	Plastic deformation/ Erosion	Mechanical/fluid motion	• Abrasive jet machining (AJM) • Ultrasonic machining (USM) • Water jet machining (WJM) • Abrasive water jet machining (AWJM)

LASER Beam Machining

Focusing solar radiation on a paper

Intensity of sun at earth's surface = 1 kW/m^2

Focusing light radiation on workpiece



Laser power density = 1.9 x 10^7 kW/m^2

- Can machine all the materials (including diamond)

What is LASER?

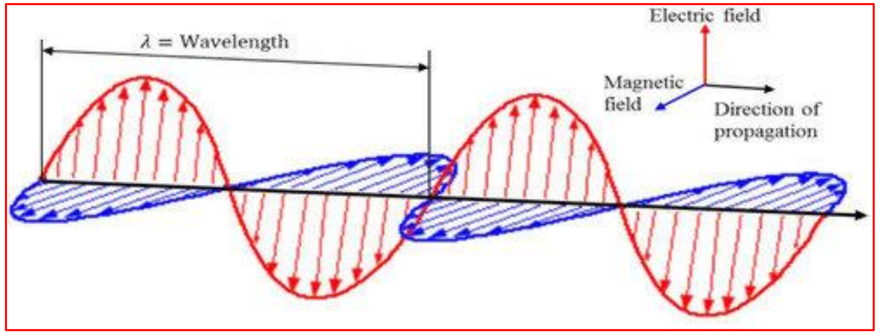
LASER is an acronym of :

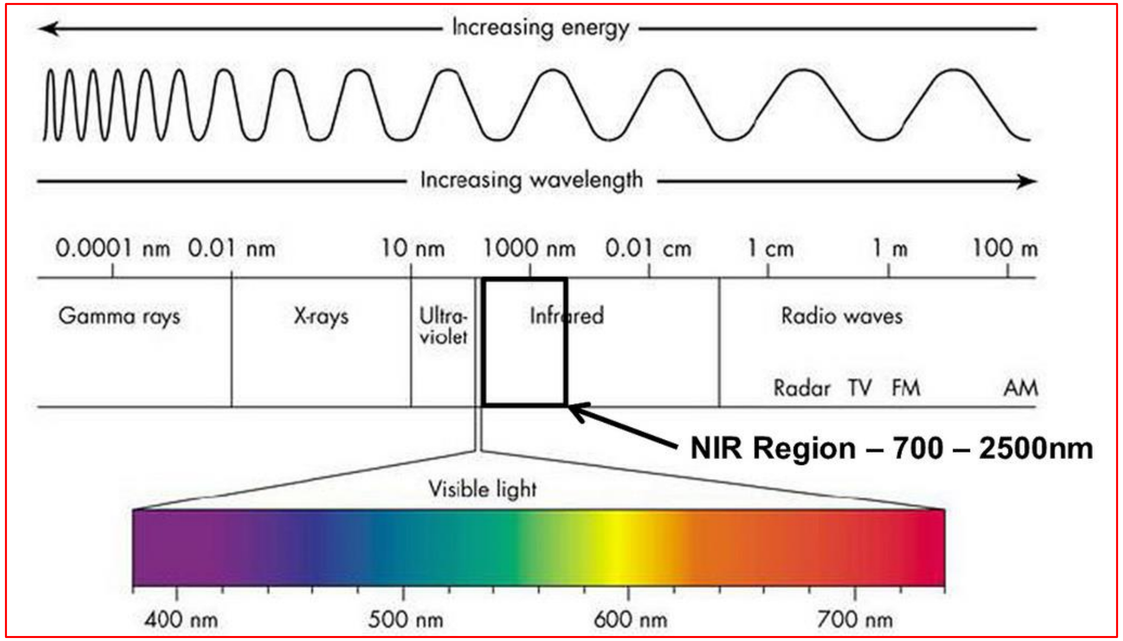
Light **A**mplification by **S**timulated **E**mission of **R**adiation

What is Light?

What is Light?

- Electromagnetic radiation.
- Electrical and Magnetic Vectors oscillating in two orthogonal planes
- Carries Energy in the direction of propagation
- Photons: massless packets of energy, each travelling with wavelike properties at the speed of light





$E = hc/\lambda$

E : energy of photon

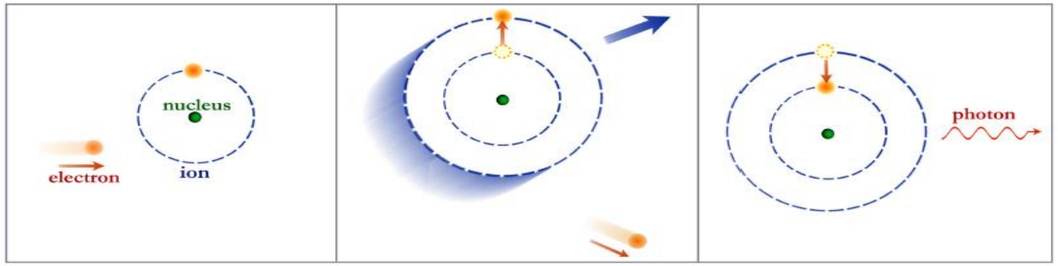
h : plank's constant

c : speed of light

λ : wavelength

How Light is emitted?

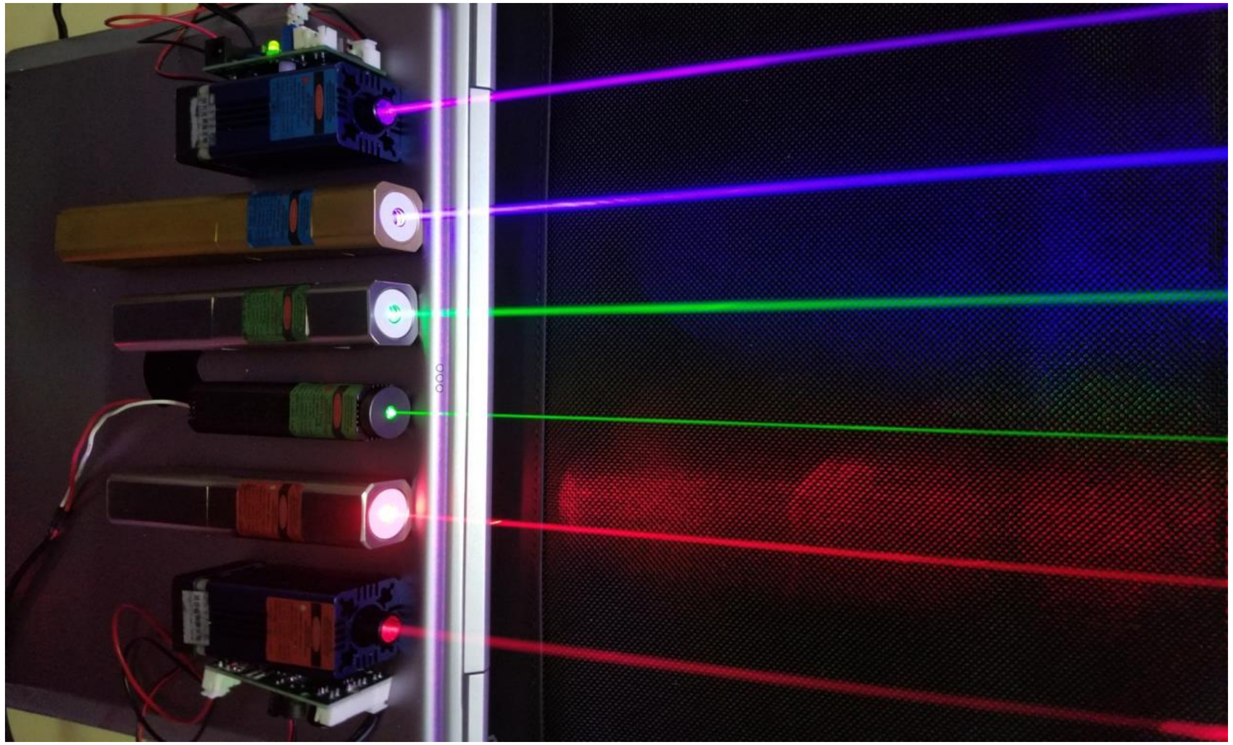
When an excited atom decays from the excited energy state to a lower energy state, the difference of energy of these states emerged out as a light wave, also known as a photon.



Characteristics of LASER

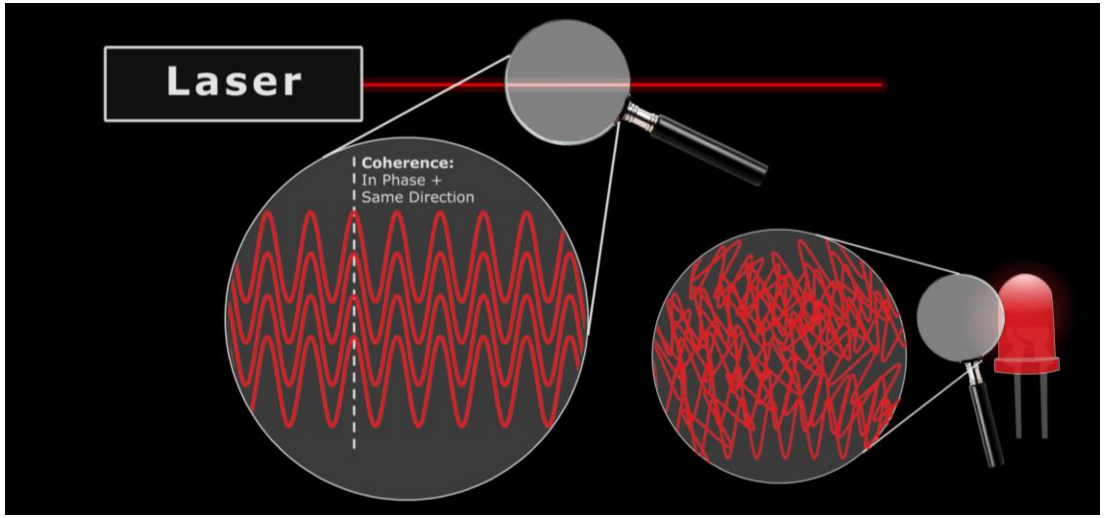
1. Lasers are monochromatic: they have single output wavelength or a pure color with an extremely narrow bandwidth.

- Depending on the laser type, they can have wavelength from ultraviolet through visible and even in the infrared portion of the electromagnetic spectrum.
- Wavelength selection is important dependent on the material being processed. Analysis of objects at a certain energy is important for research purpose.



Red (660 & 635 nm), green (532 & 520 nm) and blue-violet (445 & 405 nm) lasers

2. Highly coherent: all waves are exactly in phase with one another.



Light bulb

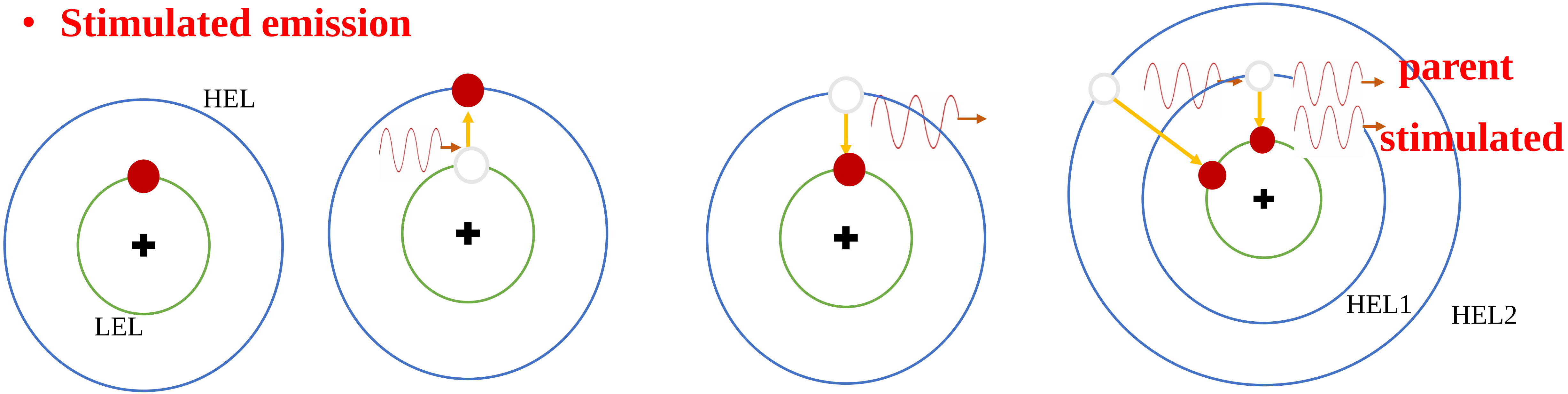
3. Lasers are highly directional/ low divergence

- Lasers have been bounced off the moon to accurately measure the distance between moon and earth.

Laser interaction with an atom

- **Spontaneous absorption**
- **Spontaneous emission**
- **Stimulated emission**

Light **A**mplification by **Stimulated Emission** of **R**adiation



A. Spontaneous absorption

B. Spontaneous emission

C. Stimulated emission

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

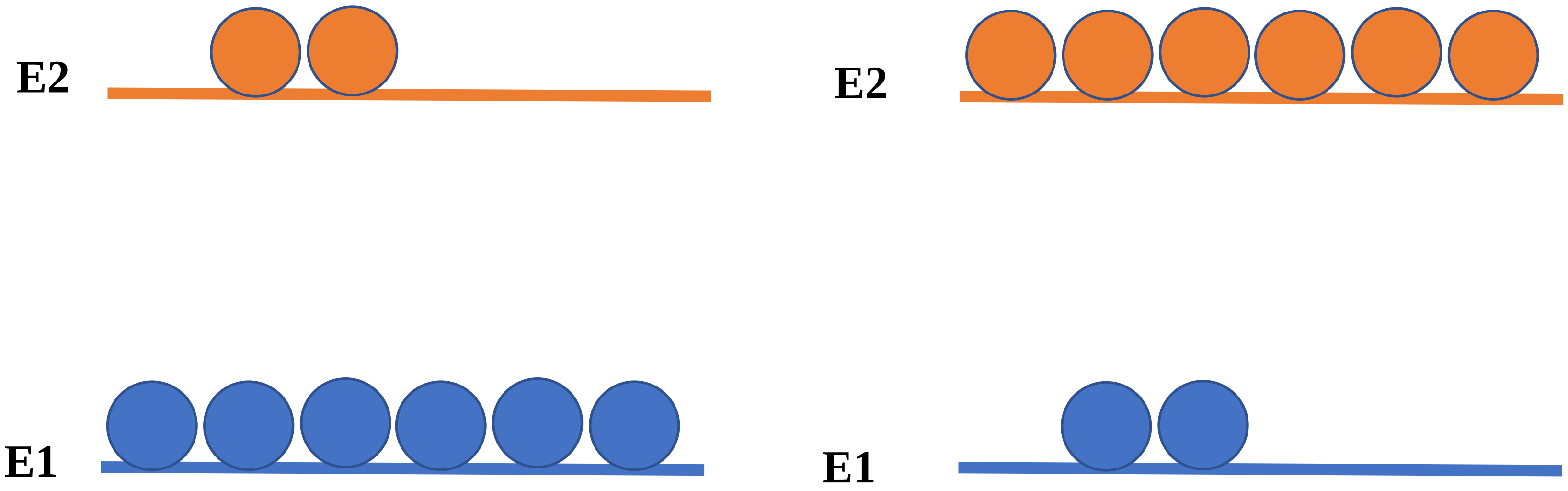
: electron , : energy photons,

Population inversion

- In normal condition: more population in lower energy levels than higher energy levels: Absorption dominates over Stimulated Emission

- Stimulated Process to dominate over Absorption Process: <u>More Population in Excited State</u>

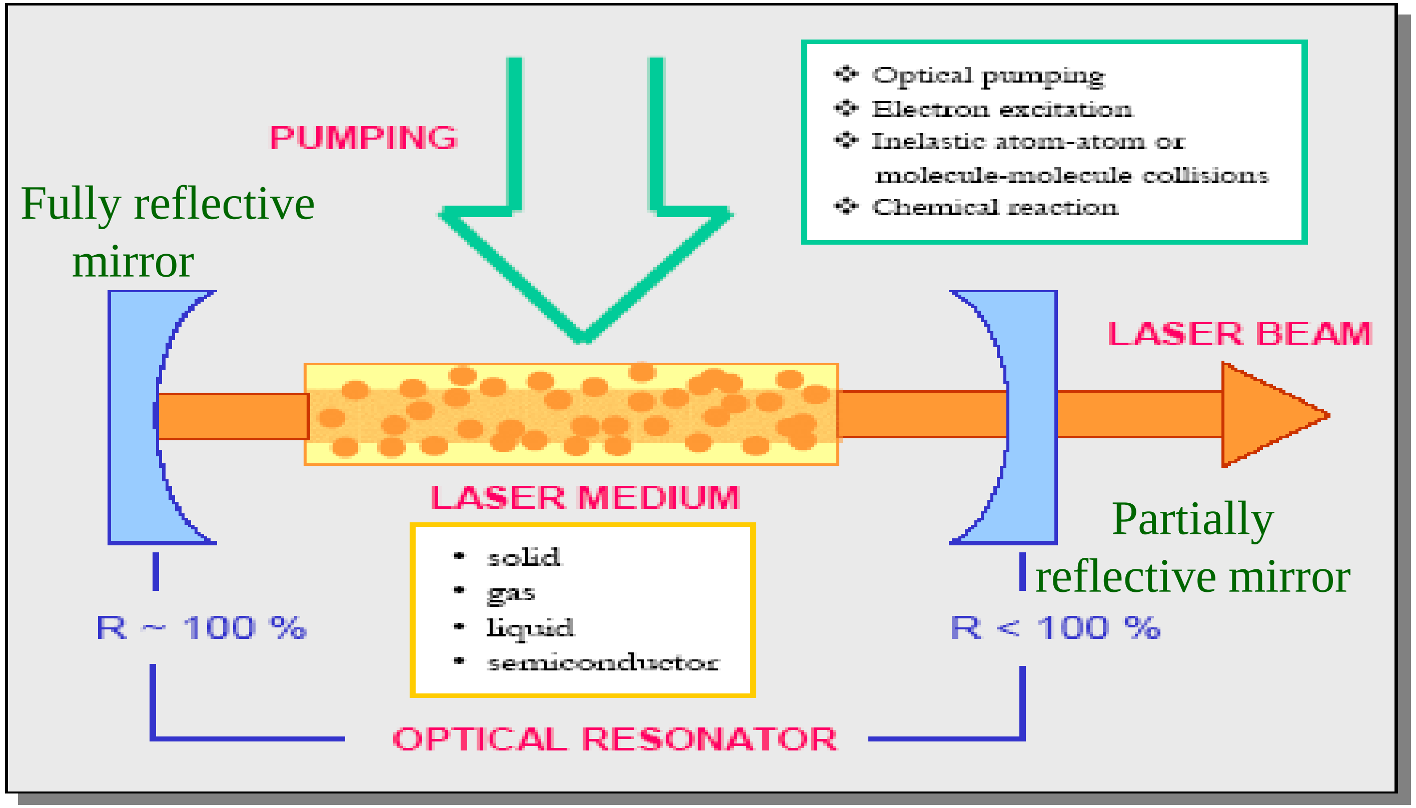
- If a significant population inversion exists, stimulated emission can produce significant light amplification.



Normal condition: N1> N2

Population inversion
N1< N2

Components of a LASER



1. Active medium

- Solid: Ruby (Cr + Al_2O_3), Nd:YAG, Optical Fiber

* Liquid: Dye Laser

* Gas: He-Ne, CO_2, Excimer Ar^+ ion

* Semiconductor Diodes

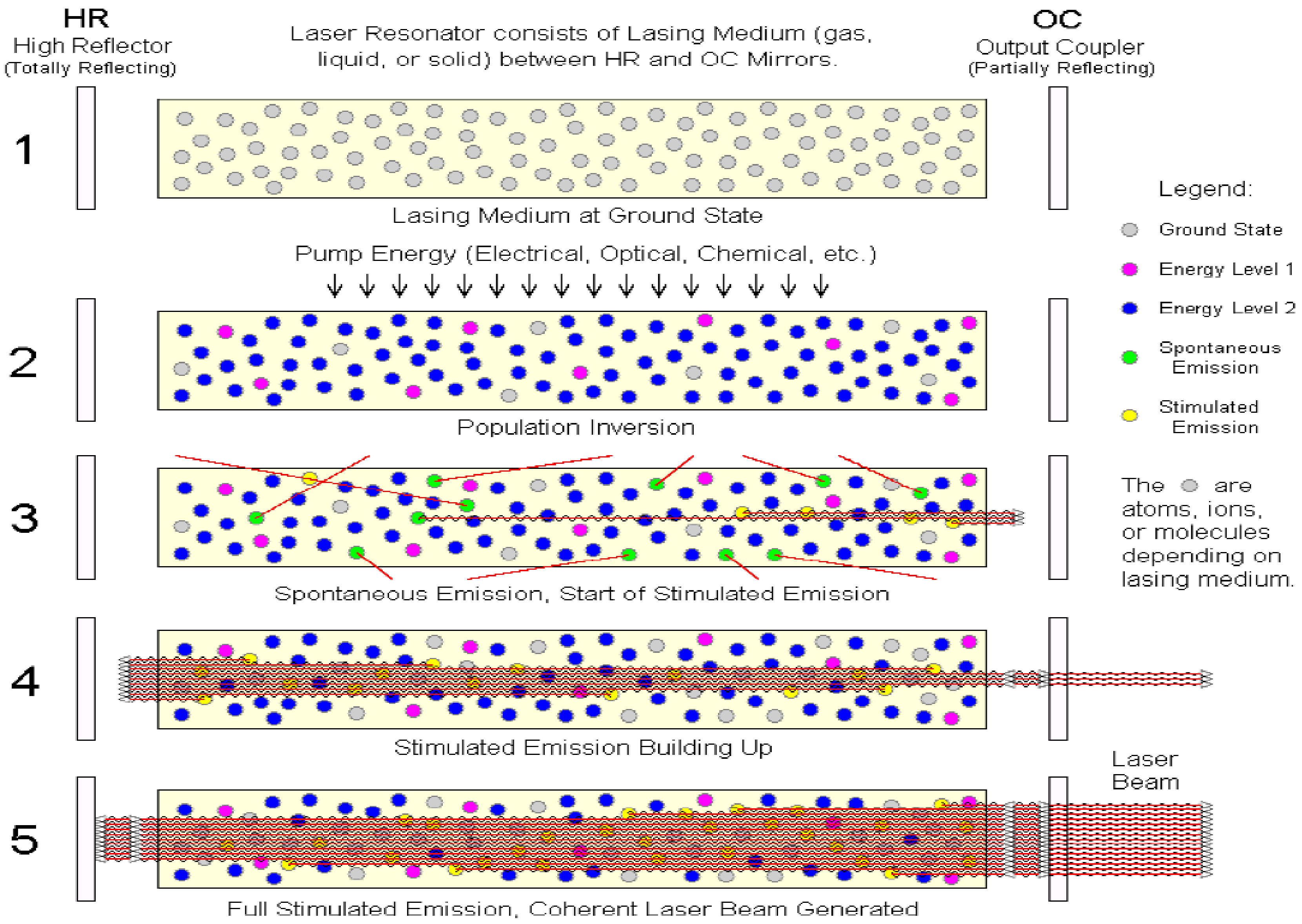
2. Excitation or Pump Source to produce population inversion in lasing medium.

* Optical Pump (Flash Lamp, Other Laser) : Solid State & Fiber Lasers
* Electrical discharge (DC, AC, RF, Pulsed) : Gas Lasers
* Current injection : Diode Lasers

3. Optical Resonator formed by a pair of parallel mirrors, one fully reflecting and other partial reflecting.

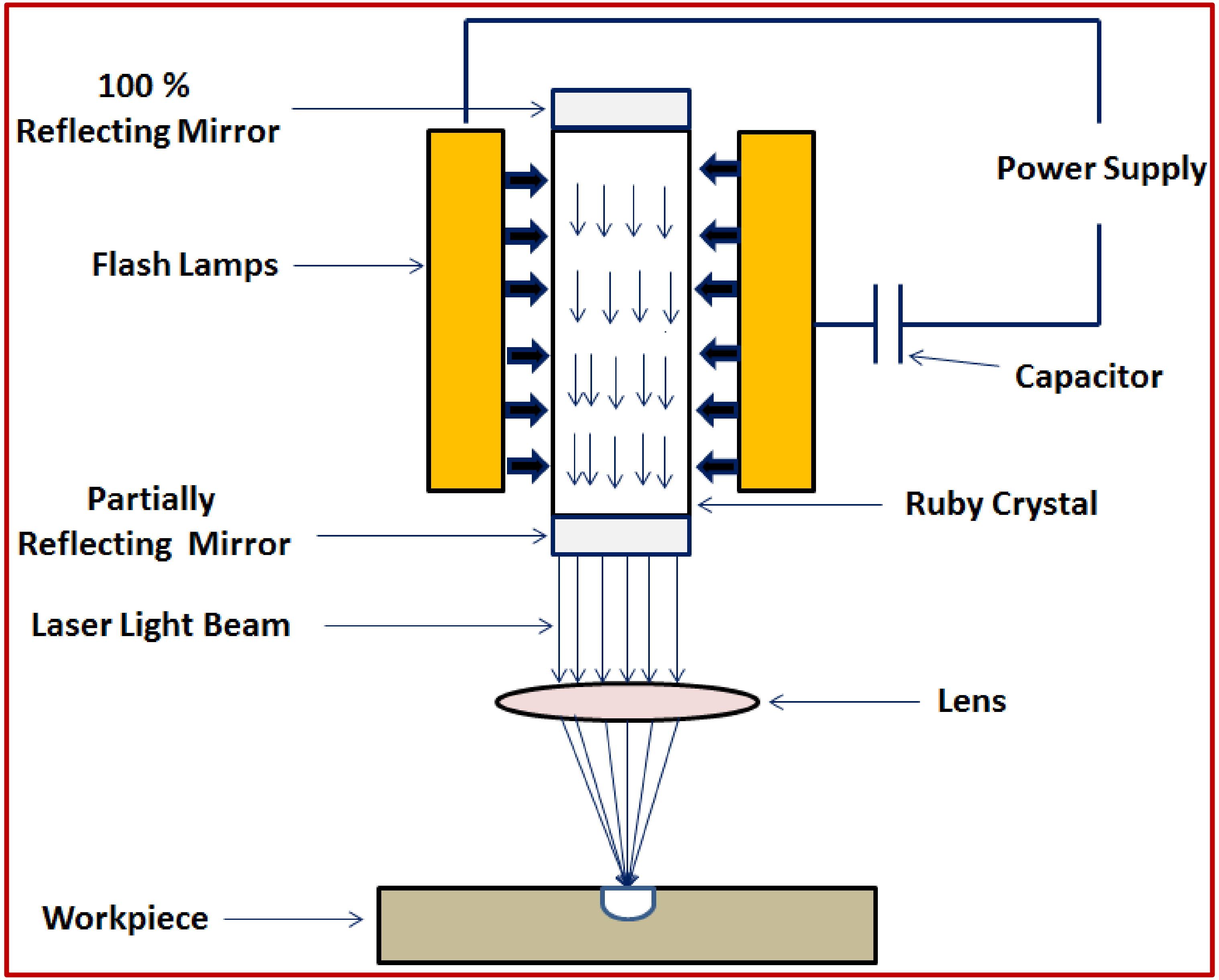
They provide feedback into the active medium and facilitates laser beam to build up. Laser beam comes out through the partial reflecting mirror.

Basic Laser operation



Basic Laser Operation

Mechanism of LBM



- Mechanism: Melting and vaporization.
- Medium : Normal atmosphere
- Tool: Laser beam

- Machining by LBM can be achieved by the following phases:
  - Interaction of laser beam with work.
  - Heat conduction and temperature rise.
  - Melting, vaporization, and ablation.

Interaction of Laser beam with Metals

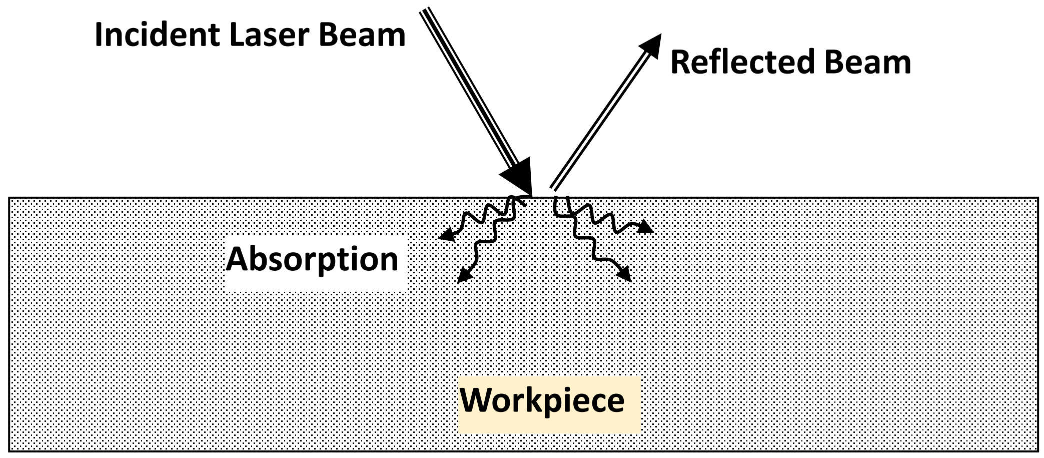
1. Metals are opaque to Laser radiation, and highly reflective (~90%), therefore good fraction of laser power is reflected.

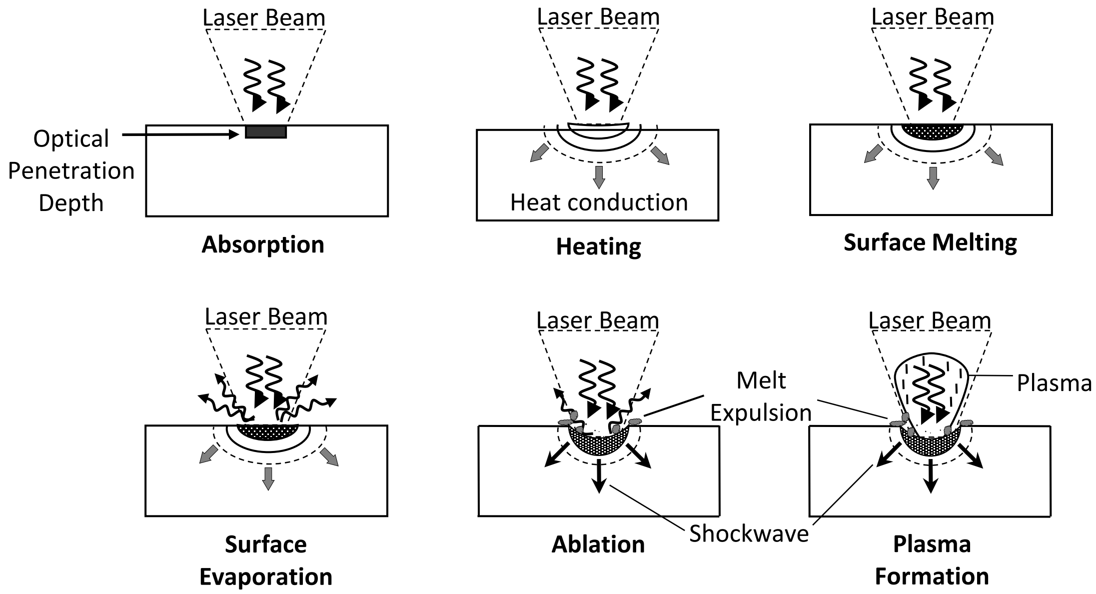
2. Remaining laser power is absorbed at the top surface within a thin layer (~10 nm).

3. With rise in surface temperature, absorptivity increases.

4. Heat conducts from the top layer into rest of the metal.

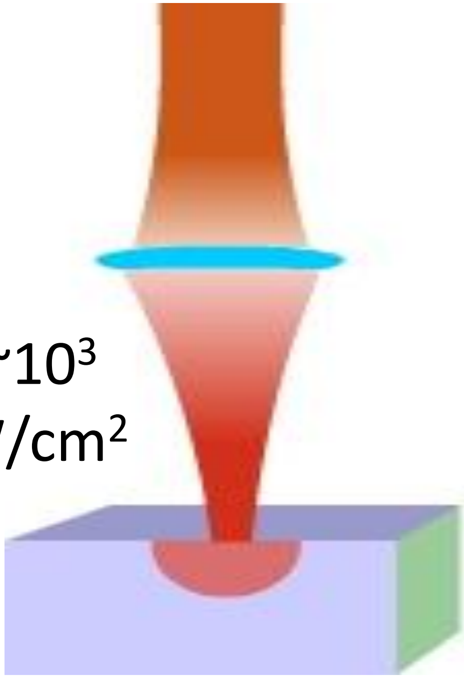
5. Depending upon the absorbed laser power density and interaction time, the top layer undergoes heating, melting, evaporation, ablation, and plasma formation.





Physical phenomenon of increasing Laser intensity

$$\text{Laser Intensity} = \frac{\text{Laser Power}}{\text{Beam Area}}$$



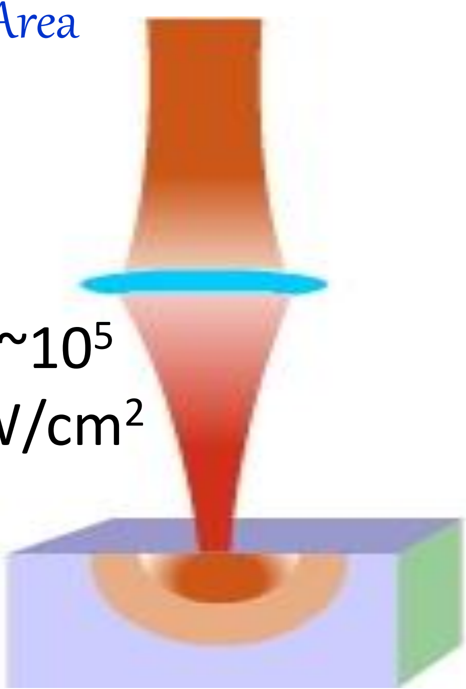
~10^3 W/cm^2

Heating of Surface layer

Surface Hardening,

Metal Forming,

Scribing

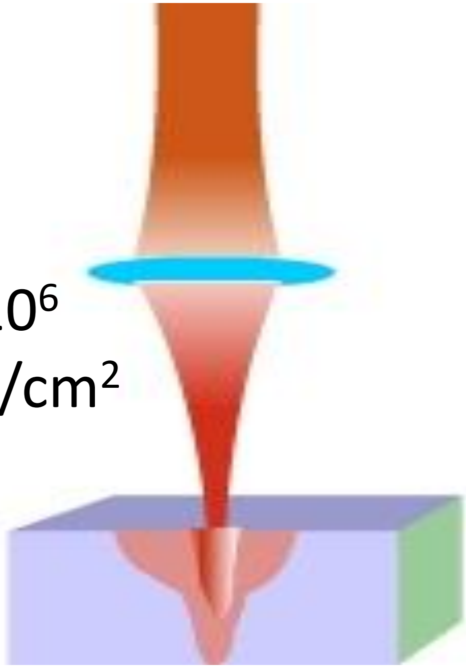


~10^5 W/cm^2

Melting

Cutting,

Conduction welding

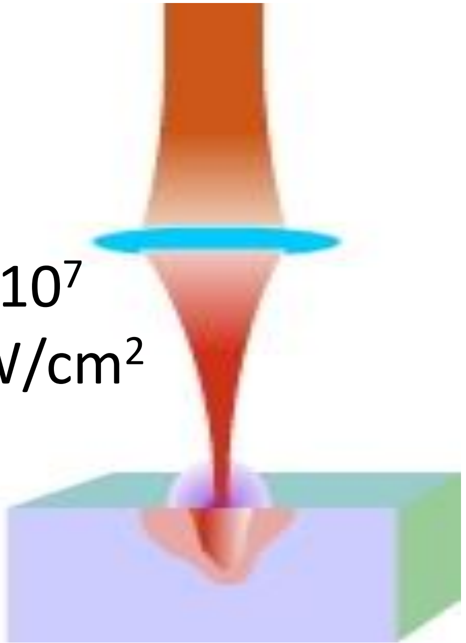


~10^6 W/cm^2

Formation of Keyhole

Drilling,

Deep penetration welding



~10^7 W/cm^2

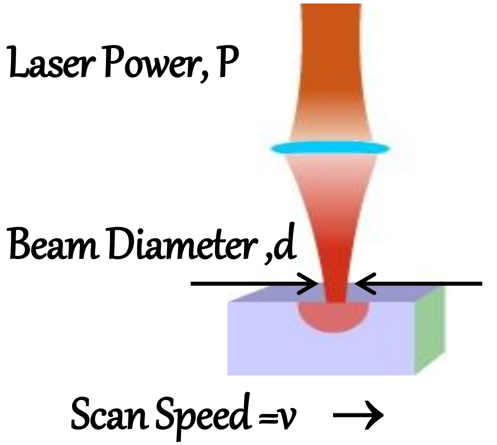
Formation of Plasma

Ionization of Vapor & Gas

Shock hardening

Laser Peening

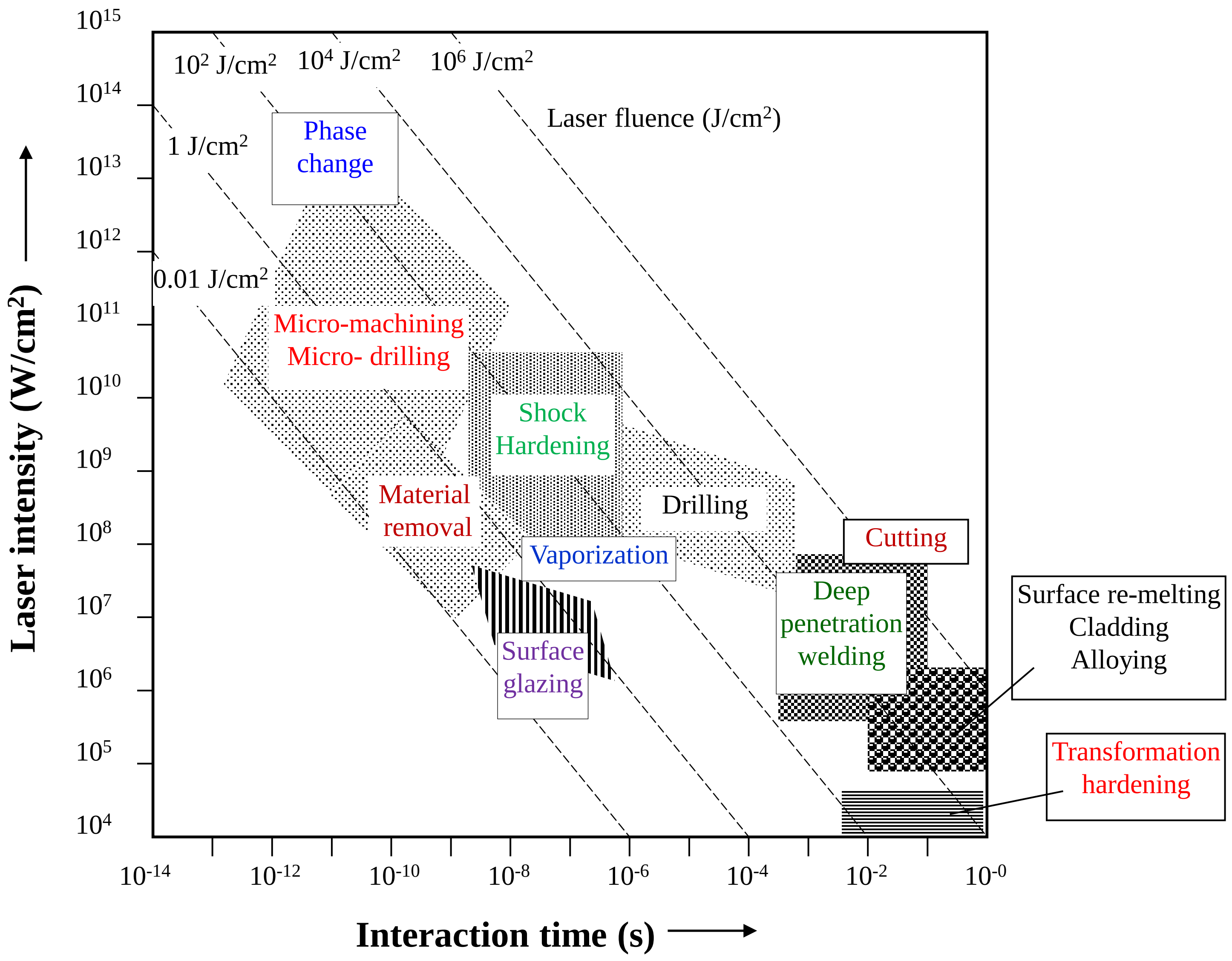
Laser Processing Parameters for Various Material Processing



$$\text{Laser Intensity} = \frac{\text{Laser Power}}{\text{Beam Area}}$$

Interaction time = Laser Pulse Duration or

$$\text{Laser Dwell time} = \frac{\text{Beam Diameter, } d}{\text{Scan Speed,} v}$$



Interaction of Laser beam with work

- Work material should not reflect too much of incident beam energy.
- The absorbed light propagates into the medium and its energy is transferred to the lattice atoms in the form of heat.
- The absorption is described by Lambert's law as follows:

$$I(z) = I(0)e^{-\mu z}$$

where, I(z) is light intensity at a depth z, I(0) is light intensity at surface and μ is the absorption coefficient.

- Most of the energy is absorbed at the top surface within a very thin layer (~ 10 nm).
- Therefore, it can be assumed that the absorbed light energy is converted into heat at the surface itself, and the laser beam may be considered to be equivalent to a heat flux.

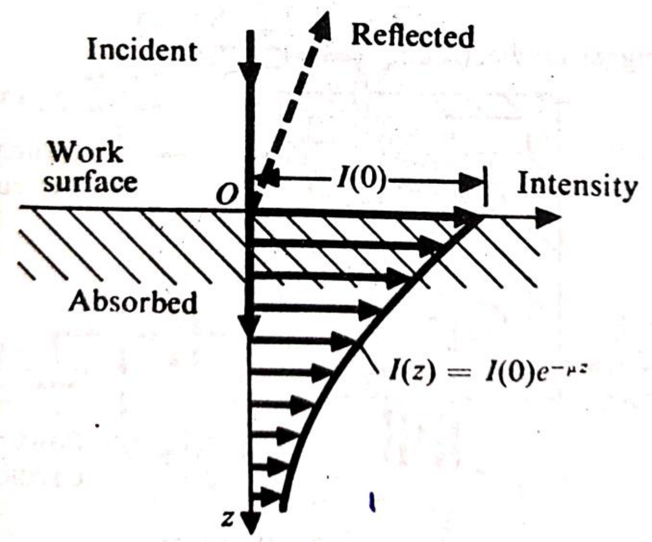


Figure: Laser beam falling on a surface and variation of intensity below surface

Heat conduction and temperature rise

- Reradiation from the surface at 3000 K ~ 600 W/cm^2
- Input flux ~ 10^5 to 10^7 W/cm^2

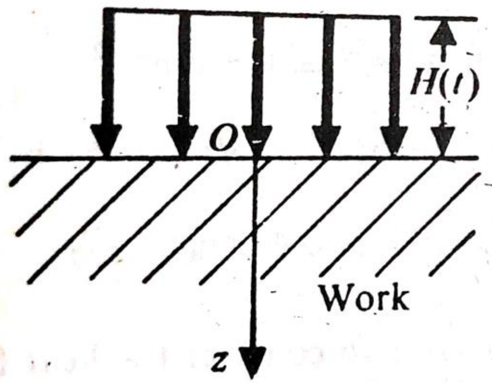


Figure:
Idealized heat flux for solving heat transfer problem

Assumptions:

- The diameter of the beam spot is larger than the depth of penetration.
- Thermal properties (such as conductivity and specific heat) are constant at different temperatures.

The equivalent heat conduction problem can be represented by a uniform heat flux H(t) at the surface of a semi-infinite body.

Heat conduction equation for the region z > 0 is as follows:

$$\frac{\partial^2 \theta}{\partial z^2} - \frac{1}{\alpha} \cdot \frac{\partial \theta\,(z,t)}{\partial t} = 0$$

where, α is thermal diffusivity and θ is temperature. $\alpha = k/\rho C_p$

Heat conduction and temperature rise

Case 1: For a deep hole

- If the molten pit/ hole is deep and narrow, the major portion of heat conduction from the molten hole takes place through the side walls.
- When the heat input rate is equal to the rate of heat loss by the molten portion, it maintains its shape and size.

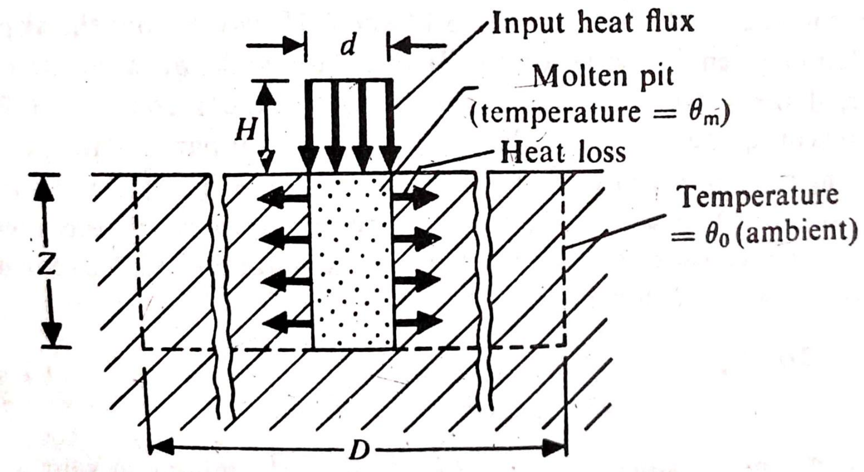


Figure: Idealized model of melting process during LBM.

- $Q_{in} = Q_{loss}$

$$\boxed{\text{Heat input rate } Q_{in} = \frac{H\pi d^2}{4}}$$

- Fourier's law of heat conduction for cylindrical coordinates:

$$Q = -kA\frac{d\theta}{dr}$$

$$Z = \frac{Hd^2}{2k\,(\theta_m - \theta_0)}$$

Where, H is the input heat flux, z is depth of machined hole,

k is thermal conductivity, θ_m is melting temperature of material, θ_0 is ambient temperature, A is area of heat flux, d inner diameter and D outer diameter of cylindrical hole.

- Let us assume Q_{loss} as rate of heat loss by molten portion inside the material

$$Q_{loss} = -kA\frac{d\theta}{dr}$$

- $-k\frac{d\theta}{dr} = \frac{Q_{loss}}{2\pi rz}$
- $-k\int_{\theta_m}^{\theta_0} d\theta = \frac{Q_{loss}}{2\pi z}\int_d^D \frac{dr}{r}$
- $-k(\theta_0 - \theta_m) = \frac{Q_{loss}}{2\pi z}[l_n]_d^D$

$$Q_{loss} = 2\pi \boldsymbol{zk}\frac{(\theta_m - \theta_0)}{l_n\,(\boldsymbol{D}/\boldsymbol{d})}$$

$l_n\,(\boldsymbol{D}/\boldsymbol{d})$ =4 (as D = 55d from experiments)

$$\boxed{Q_{loss} = \pi \boldsymbol{zk}\frac{(\theta_m - \theta_0)}{2}}$$

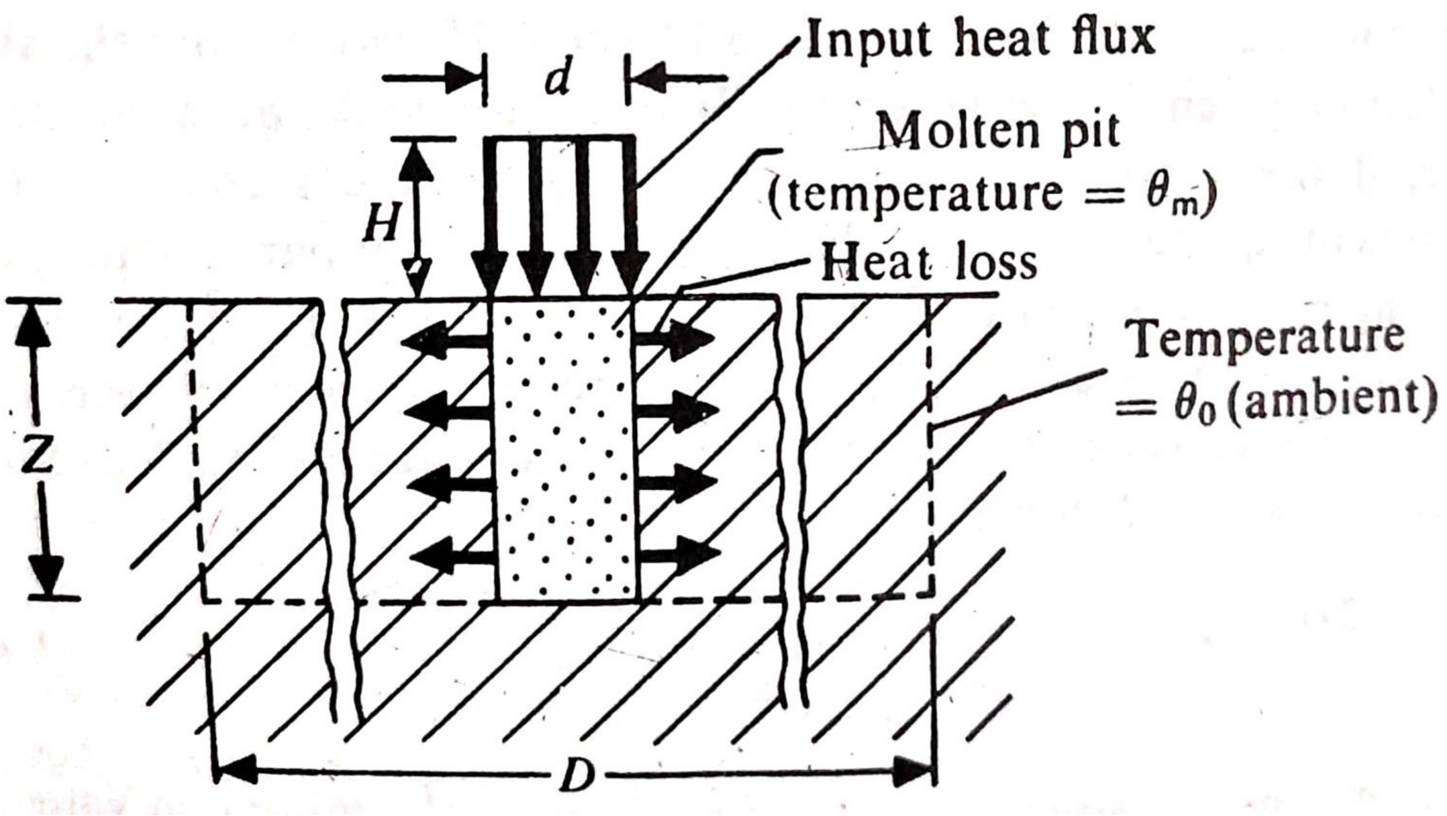


Figure: Idealized model of melting process during LBM.

- Equating heat input rate to heat loss rate:

  - $Q_{in} = Q_{loss}$

$$\frac{H\pi d^2}{4} = \pi z k \frac{(\theta_m - \theta_0)}{2}$$

- Finally, the depth of molten pit, which can approximately represent the depth of the hole machined with a medium intensity beam, is given by:

$$\mathbf{Z = \frac{Hd^2}{2k\,(\theta_m - \theta_0)}}$$

Note: When the beam intensity is very high (≥10^7 W/cm^2), heating is very rapid and incident beam heats up the surface quickly and vaporize it. Above mechanism is invalid.

The rate of heat input required to vaporize the material is: $\mathbf{H \approx vL}$

Where, v is the velocity with which the surface recedes and L is the amount of energy to vaporize a unit volume of material.

Heat conduction and temperature rise

- At the surface (z = 0)

$$\frac{\partial\theta}{\partial z} = -\frac{1}{k}\, H(t)$$

where, k is thermal conductivity.

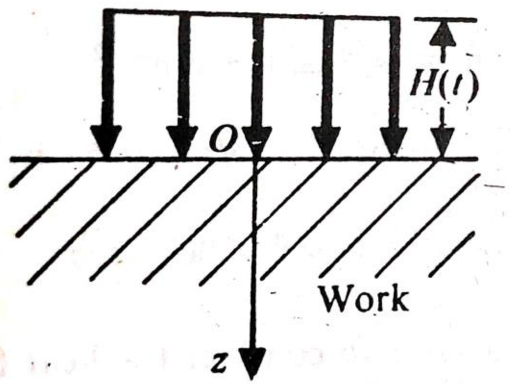


Figure: Idealized heat flux for solving heat transfer problem

Case 2: At t = 0, i.e., when the heat flux just started. Assuming temperature of the body is zero. Solution of the equation:

$$\theta\,(0, t) = \frac{2H}{k}\sqrt{\left(\frac{\alpha t}{\pi}\right)}$$

$$\mathbf{t_m} = \frac{\pi}{\alpha}\,\frac{(\mathbf{k}\theta_m)^2}{(2H)^2}$$

where t_m is the time required for the surface to reach melting temperature and θ_m is the melting temperature.

Heat conduction and temperature rise

Case 3: Considering heat flux to be on a circular spot with a diameter equal to that of the focused beam.

- If the beam diameter is d and the heat flux is uniform, both in space and time.
- Minimum value of H to attain the melting temperature is given by:

$$\mathbf{H_{cr}} = \frac{2k\theta_m}{d}$$

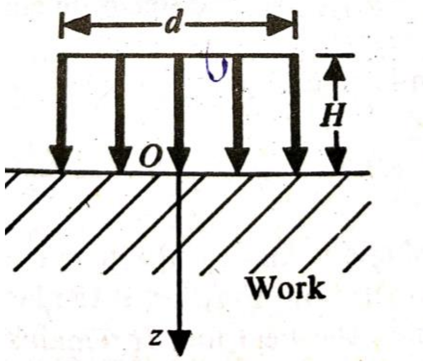


Figure: Idealized heat flux, uniform both in space and time.

Numerical

Q1: A laser beam with a power intensity of 10^3 W/mm^2 falls on a Tungsten sheet. Find the time required for the surface to reach the melting temperature. The given thermal properties of tungsten are melting temperature = 3400 °C, thermal conductivity = 2.15 W/cm- °C, volume specific heat = 2.71 J/cm^3- °C. Assume that 10% of the beam is absorbed.

Solution:

$$t_m = \frac{\pi}{\alpha} \frac{(k\theta_m)^2}{(2H)^2}$$

Given data: θ_m = 3400 °C, k= 2.15 W/cm- °C, volume specific heat = 2.71 J/cm^3- °C

$\alpha = k/Q_v = 2.15/2.71$ cm^2/sec = 0.79 cm^2/sec

H = 0.1 * 10^3 * 100 W/ cm^2

t_m = 0.53 sec

Numerical

Q2: A laser beam with a power intensity of 10^7 W/cm^2 is used to drill holes in a tungsten sheet of 0.5 mm thickness. The drill diameter is 200 µm. If 30000 joules/cm^3 are required to vaporize tungsten, estimate the time required to drill a through hole. The efficiency may be taken to be 10 %.

Solution:

$$\mathbf{H \approx \boldsymbol{vL}}$$

Where, v is the velocity with which the surface recedes and L is the amount of energy to vaporize a unit volume of material.

Given data: H = 10 % of 10^7 W/cm^2, z = 0.5 mm, d = 200 µm, L = 30000 joules/cm^3

v = H/L = 333 mm/sec

So, the time required to drill a hole:

t = z/v = 0.0015 sec = 1.5 ms

Laser Cutting

Laser cutting dominants the industrial laser applications & has more than 75% of share of all LM applications.

- Fast cutting with higher quality than other competing processes.

Basic Principle : Melting with a focused laser beam and molten material ejection by a high-pressure gas jet.

- CO_2 Laser (10.6 μm), NdYAG & Fiber Lasers (1.06 μm)
- Laser Power = 500-5000W
- Focal spot size ~ 0.1 – 0.3 mm
- Power density of 1kW power at focal spot of 0.3mm ~ 1.4 $X10^6 W/cm^2$
- Effect on material

  * Melting

  * Vaporization
- Pressurized co-axial gas jet ejects the molten / vaporized material

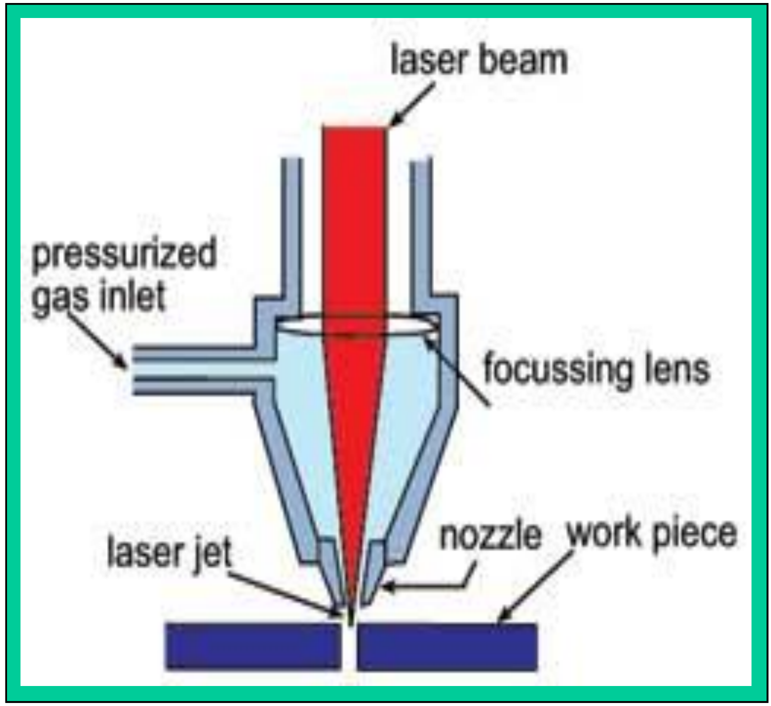
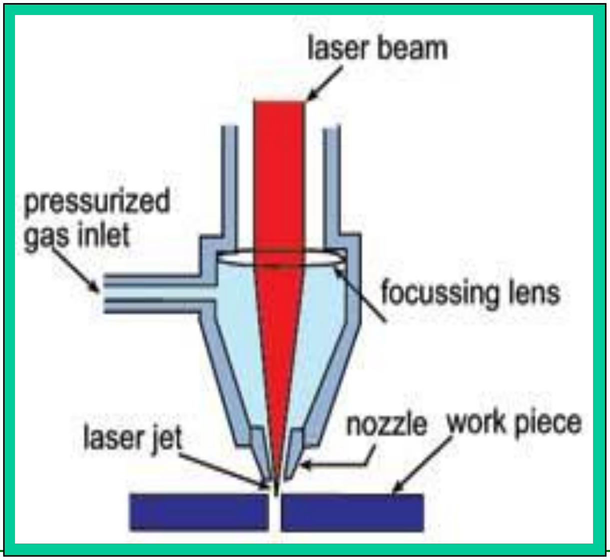
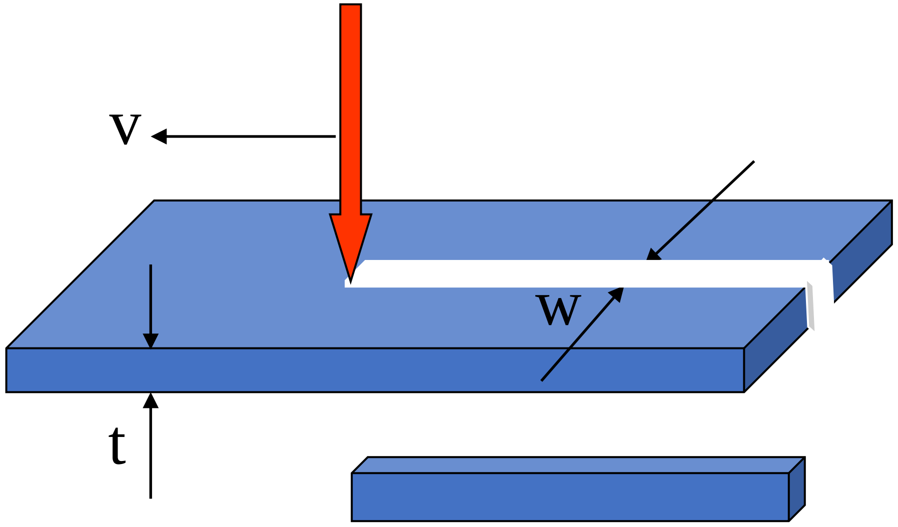


Figure: Schematic of laser cutting

Energy balance in Laser Fusion Cutting





Energy required for cutting ($E_{cutting}$) = $E_{\text{reaching to melting temperature from ambient temp}}$ + $E_{\text{phase change from solid to liquid}}$ + $E_{\text{phase change from liquid to vapour}}$

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

Moving laser for cutting

where,
η = (1-R) Laser efficiency,
P = Laser power,
t = Sheet thickness,
w = cut or kerf width,
v = cutting speed,
L_f = latent heat of fusion,
L_v = latent heat of vaporization,
m'=Fraction of metal evaporated,
ρ = density,
ΔT = Temperature raise,
C_p = Specific Heat,
m = mass of material removed

Energy balance equation: No conduction loss

$$\eta P = \dot{m}\,(C_p.T_m + L_f + m' L_v)$$

$$\eta P = w.t.v.\rho\,(C_p.T_m + L_f + m' L_v)$$

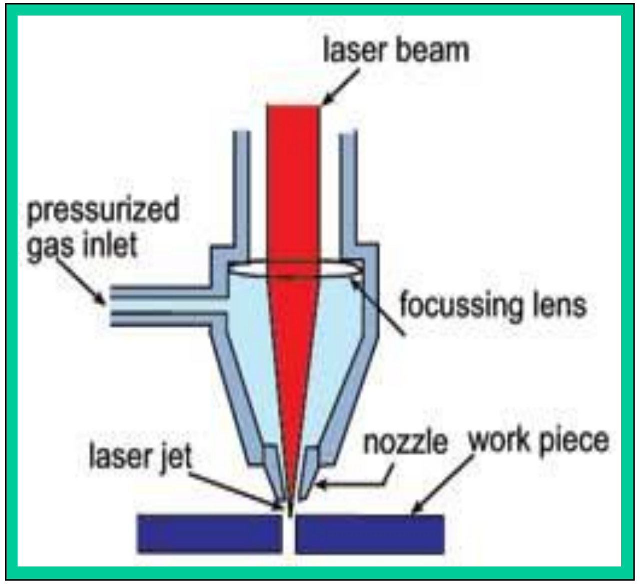
In cutting, $m' = 0$

Cutting speed, $v = \eta P / \{w.t.\rho\,(C_p.T_m + L_f)\}$

$P/v.t = w.\rho\,(C_p.T_m + L_f) / \eta = S$,

S is constant for a constant w & a given material Called as **"Severance Energy"** in (J/mm^2)

Laser cutting process parameters



- Laser Power,
- Cutting Speed,
- Laser focal spot diameter
- Spot location w.r.t. workpiece surface
- Assist gas type and its pressure,
- Standoff distance between Nozzle tip and workpiece,
- Cutting nozzle type (Cylindrical/ Conical) & its opening diameter.

Quality factors in Laser Cutting

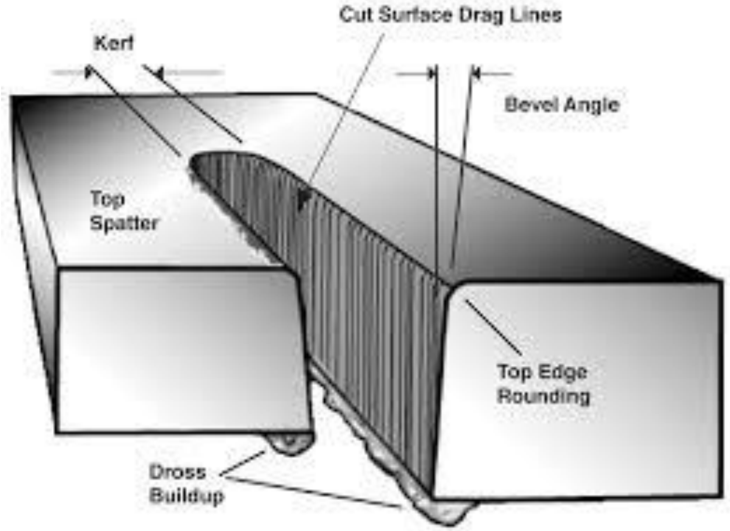
➢ Very narrow Kerf-width – material saving. (kerf is the width of cut opening)

➢ Cut edge can be smooth and clean: no postprocessing needed.

➢ No edge burr : dross adhesion can be avoided.

➢ Very narrow heat affected zone.

➢ Blinds holes are possible – in wood and acrylic.



https://www.thefabricator.com/thewelder/article/cutting weldprep/troubleshooting-cnc-plasma-cutting-part-ii

Laser Cutting

Process Capability:

- All most all materials e.g. metal, non-metals like ceramics, glass, concrete, rubber, fiber-glass, plastics, textile, lather etc. can be cut by lasers.

- Steel sheets of thickness 25 mm can be cut at 1-2 m/min speed with high power (2-4 kW) CO_2, Nd:YAG and Fiber lasers and O_2 gas assist.

- Integrated with CNC machine it can cut any complex contour.

Practical Applications:

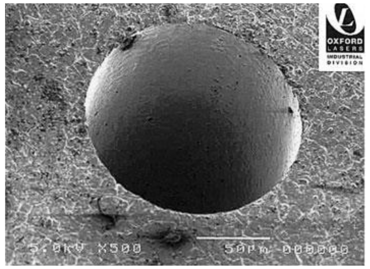
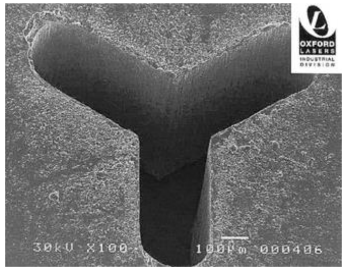
- Automobile industries, Rail-coach factory, Ordnance factory, Textile, Leather, Furniture, Ship-building, Nuclear and Aerospace industries, and many mechanical & metallurgical engineering job shops are using lasers in their production line to cut variety of materials.

- Cutting of diamonds is one of the most popular applications in India.

Laser Drilling

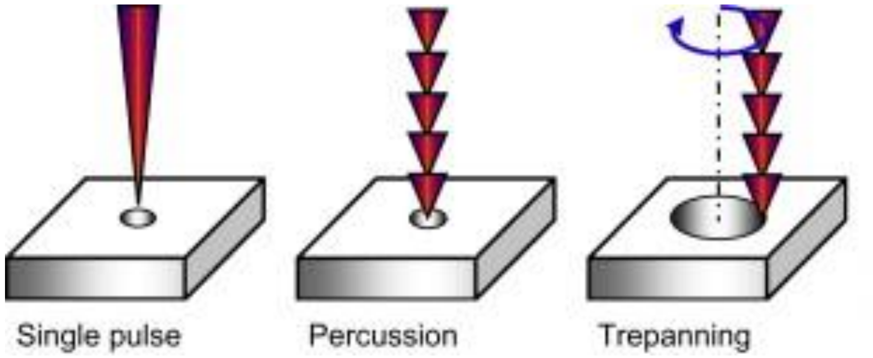
Material Removal Mechanism:
Vaporization & Melt ejection by recoil pressure of vapour

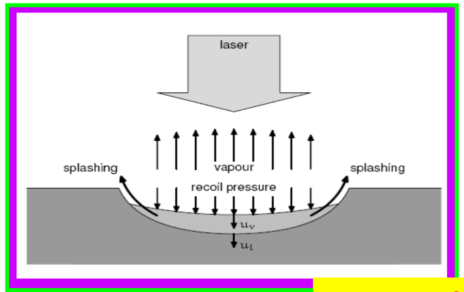
- Laser drilling was the first industrial application by Western Electric, using a ruby laser in 1965 to drill holes in diamond dies for wire extrusion. (Cutting in 1970)
- The importance of laser drilling as an industrial process has led to many variations on how to achieve quick, high-quality holes with good repeatability.
- **Single shot drilling:** One pulse makes and finishes the hole.
- **Percussion:** Single or multiple shot with no movement of the workpiece/beam.
- **Trepanning:** Rotating the beam around the perimeter of the hole, a form of cutting.

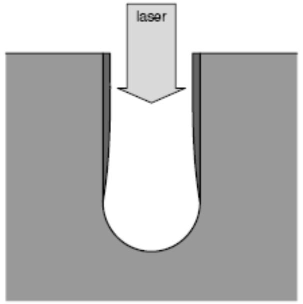



(http://www.designforlasermanufacture.com and Oxford Lasers)

Type of holes:
1) Normal to the surface.
2) At an angle to the surface.
3) Blind holes



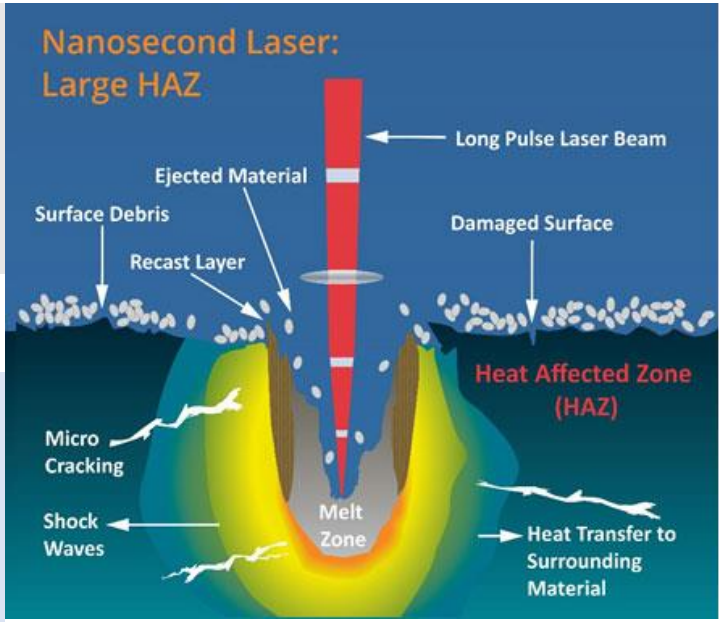


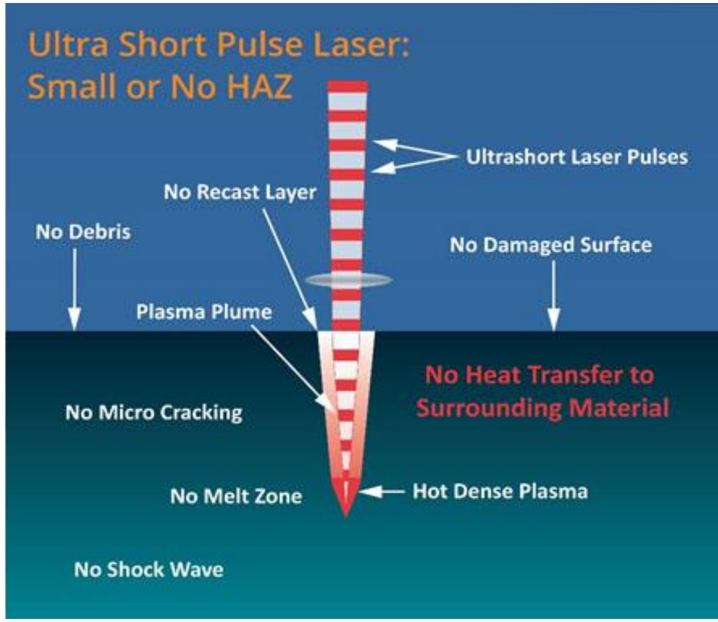


Recast layer formation

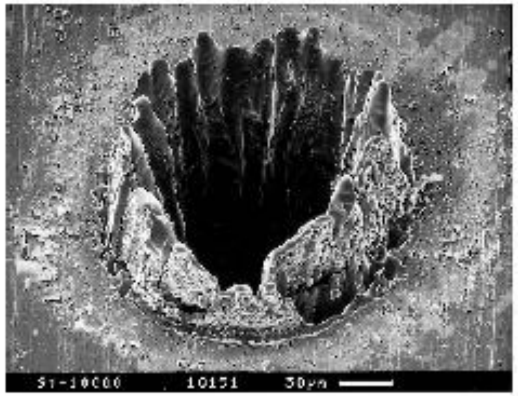
Drilling with Long and Ultra-short Laser Pulses

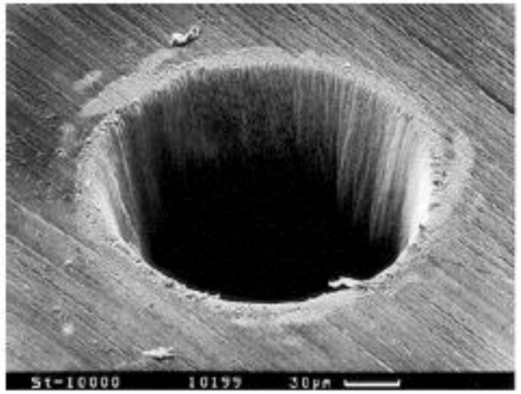
- Longer pulses continuously heat the material during the pulse duration.
- Heat conduction: HAZ, recast layer, microcracks.



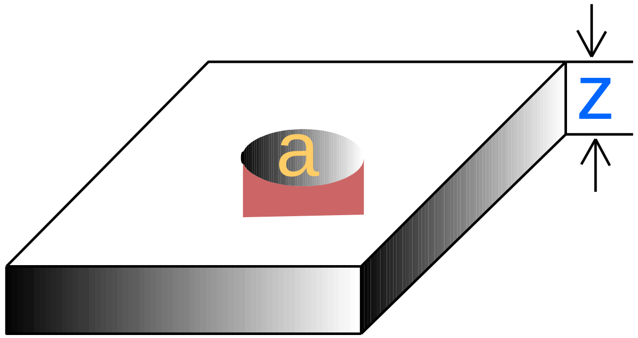


- Ultrashort laser pulses : a few ps or below
- Due to the extremely short pulse duration, only electrons are heated at first.
- Energy transfer to the lattice takes place on a timescale longer than the pulse itself. - Heat conduction is limited.
- This finally leads to ablation within a well-defined region with minimum thermal and mechanical damage to the surrounding





Energy balance consideration in Laser Beam Drilling



Energy required for drilling ($E_{drilling}$) = $E_{\text{reaching to vaporization temperature from ambient temp}}$ + $E_{\text{phase change from solid to liquid}}$ + $E_{\text{phase change from liquid to vapour}}$

$$U = \left(C_p T_v + L_m + L_v\right) \cdot \rho \pi a^2 z$$

$$\frac{dU}{dt} = \left(C_p T_v + L_m + L_v\right) \rho \pi a^2 \frac{dz}{dt}$$

$$\frac{Power}{\pi a^2} = irradiance \quad I$$

$$V_v = \frac{I}{\rho\left(C_p T_v + L_m + L_v\right)}$$

(mass = density * volume)
Laser position - fixed

$$t_{hole} = \frac{z}{V_v}$$

We can assume C_p constant. $\frac{dU}{dt}$ is the power and $\frac{dz}{dt}$ is the vapourization front velocity V_v

e.g. Drill hole in 1 mm thick of metal

$I = 10^6$ W cm^{-2} = 10^{10} W m^{-2}

V_v =1/6 m s^{-1}

t_{hole} ~ 6 x 10^{-3} s

C_p ~ 500 J kg^{-1}K^{-1} for metals

T^V ~ 2 x 10^3 K

L_V ~ 5.0 MJ kg^{-1}

ρ~ 10^4 kg m^{-3}

Benefits of Laser Beam Drilling

- Non-contact drilling (no tool wear or breakage, no material distortion)
- Highly accurate and consistent results
- Precise control of heat input
- Hard materials like diamonds can be easily drilled
- Ability to produce small holes with high aspect ratios
- Ease of programming and adaptability to automation
- Increased production rates with faster setup times and less tooling
- Versatility (the same tool can also be used for cutting and welding
- Ability to process a wide range of materials

Limitations of Laser Beam Drilling

- Laser holes are tapered to some extent (approximately 1% of the drill dep
- Cannot drill a blind hole to a precise depth
- Not efficient for heat sensitive material
- Slower processing of large holes due to trepanning

Applications

- Cooling holes in military engines
- Electronic package
- Inkjet nozzles
- Surgical tooling
- Cooling holes in turbine blades and combustion chamber
- Irrigation pipes

Laser Surface Treatment

- Laser Surface Transformation Hardening.
- Laser Melting & Re-solidification.
- Laser Surface Alloying.
- Laser Surface Cladding.

Ex:

- **Titanium:** Surface alloying with N_2 – wear resistance
- **Cast Iron:** Surface alloying with Cr, Si or C
- **Steel:** Alloying Fe with Cr, Mo, B , Ni, etc.

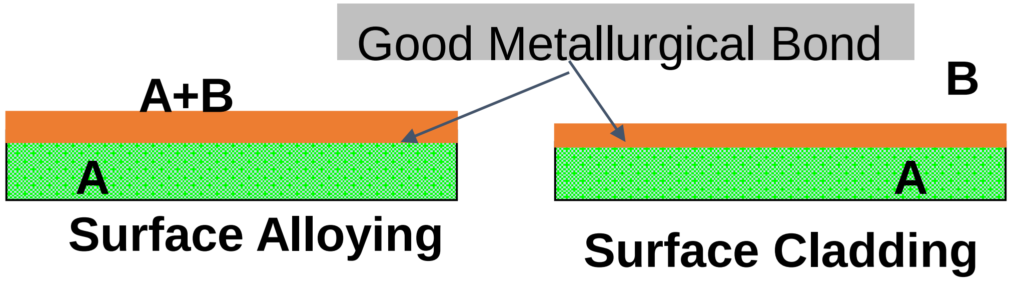
Need for Surface Treatment

To improve

- Hardness,
- Strength,
- Wear resistance,
- Corrosion resistance and
- Fatigue life
- To reduce friction

Laser Surface Alloying: A thin layer along with appropriate alloying elements are melted by the laser beam to form an alloyed layer

Laser Cladding deposition of a new material to the existing surface with excellent metallurgical bonding with the substrate and with minimum dilution of substrate material.

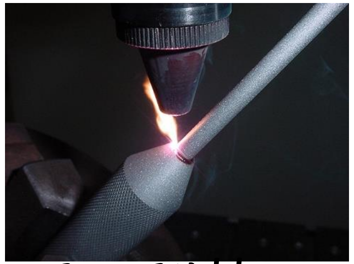


Applications of Laser in Manufacturing

- Laser Cutting of Metal Sheets, Glass, Wood, Plastics, Textiles, Rubber, Ceramic, Marble etc.

Laser Cutting

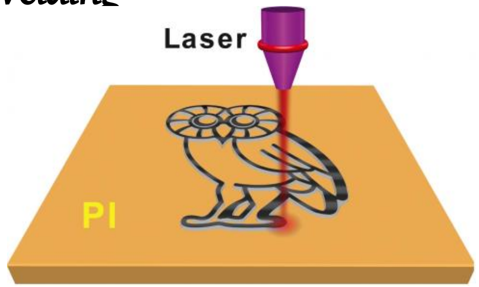
- Laser Welding of Similar & Dissimilar metals & Alloys.



Laser Welding

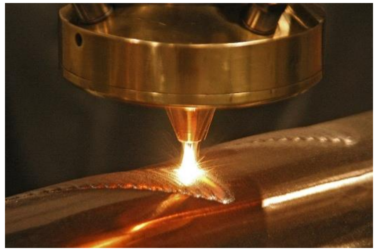
- Laser Surface Hardening

- Laser scribing, marking, engraving



Laser Scribing

- Laser Surface Cladding



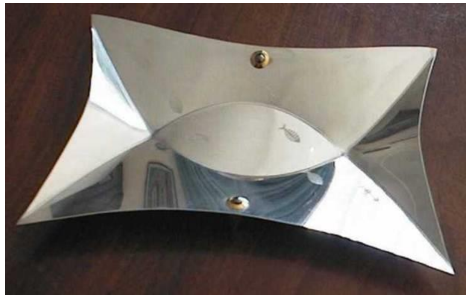
Laser Cladding

- Laser Rapid Manufacturing

- Laser polymerization

Laser Rapid Prototyping

- Laser Metal Forming



Laser Forming

- Laser Surface Alloying

Summary of Laser Beam Machining

- **Mechanism:** Melting , vaporization, and ablation
- **Medium** : Normal atmosphere
- **Tool:** Laser beam
- **Material application:** All materials
- **Critical parameters:** Laser beam diameter, laser intensity, melting temperature.
- **Applications:** wide variety of applications (drilling, cutting, welding, surface treatment, additive manufacturing, etc.)
- Advantages: Rapidity, Accuracy, High production rate, Complex shape/size machining, machining of all materials irrespective of their mechanical properties, etc.
- **Limitations:** High power consumption, Less efficiency, Unsuitable for cutting -high thermal conductivity and high reflectivity materials

THANK YOU!