

Advances in Welding and Joining Technologies

Swarup Bag

**Department of Mechanical Engineering
Indian Institute of Technology Guwahati**

Module 2

Laser and Electron Beam Welding

- ✓ Principle of laser
- ✓ Types of lasers and their applications
- ✓ Keyhole and conduction mode laser welding
- ✓ Laser welding of metals
- ✓ Pulse shaping in laser welding
- ✓ Laser assisted hybrid welding
- ✓ Electron beam welding

Introduction

Light Amplification by Stimulated Emission of Radiation

At the surface the concentration of light energy converts into thermal energy (heat)

The heat causes the surface of the material to heating or melting or vaporization

Manufacturing industry – Machining, welding, cutting, surface modification, additive manufacturing, heat treatment

Measurement

Medical applications

Laser nuclear fusion

Communication, laser printing

CDs and optical discs

Barcode scanners

Facts about Laser

Laser Components

Lasing Medium:

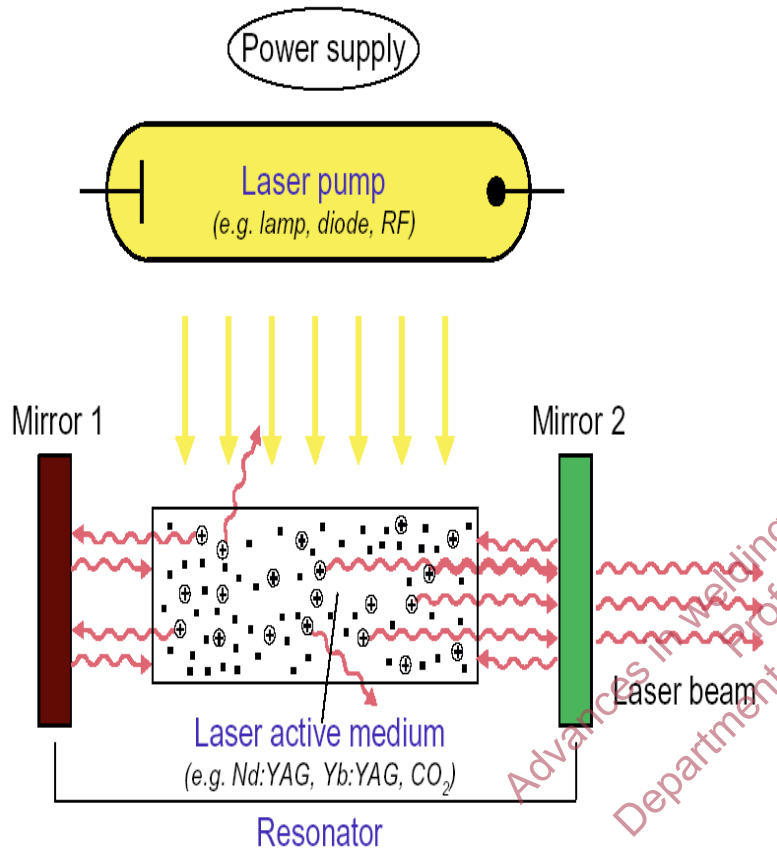
Provides appropriate transition and determines the wavelength (it must be in a metastable state)

Pump:

Provides energy necessary for population inversion

Optical Cavity:

Provides opportunity for amplification and provides a directional beam (with defined length and transparency).



Properties of Laser

Coherent (synchronized phase of light)

Collimated (parallel nature of the beam)

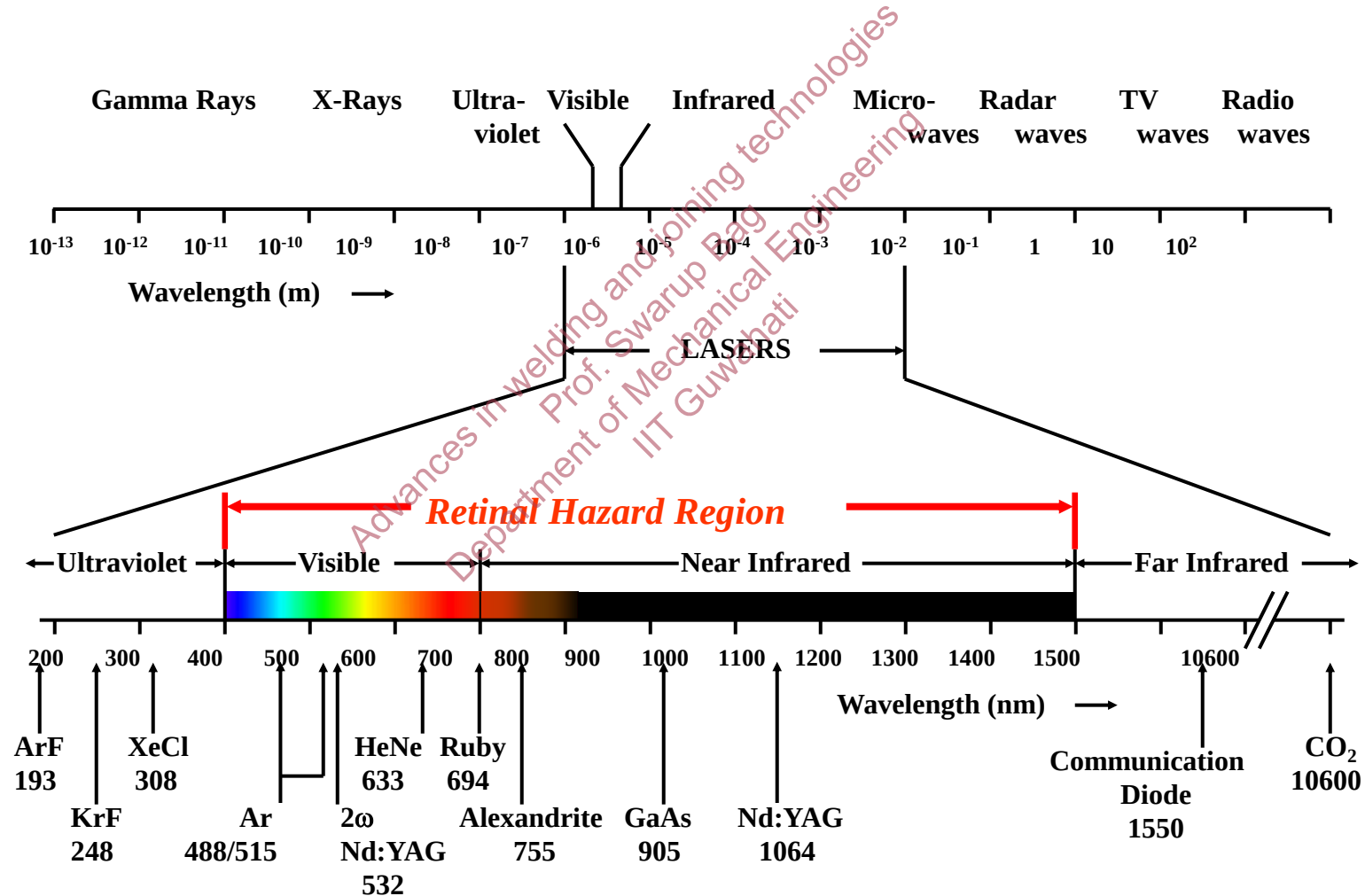
Properties of Laser

Monochromatic (single wavelength)

High intensity ($\sim 10^{14} \text{ W/m}^2$)

Facts about Laser

Laser spectrum: Lasers operate in the ultraviolet, visible, near infrared, and far infrared regions of the spectrum



Facts about Laser

Nd:YAG (Rod Laser) $\lambda = 1064 \text{ nm}$

Yb:YAG (Disc Laser) $\lambda = 1030 \text{ nm}$

CO₂ (Gas Laser) $\lambda = 10600 \text{ nm}$

Characteristics of laser light

Many colors

Many directions

Many phases

One color: select laser for application

One direction: can capture all the beam energy

One phase: maximum energy at workpiece

Principle of Laser

- ✓ Energy transfer mechanism is different from arc welding process
- ✓ Absorption of energy — laser-matter interaction
- ✓ Laser output - not electrical in nature - Eliminates any effect of magnetism
- ✓ Not require a flow of electrical current - not limited to electrically conductive materials
- ✓ doesn't require a vacuum and does not produce x-rays

Types of laser

Numerous types and designs of lasers are steadily increasing

Solid-state lasers: use a crystalline or glass rod which is "doped" with ions that provide the required energy states. Neodymium is a common "dopant" in various solid-state laser crystals, including yttrium aluminium garnet (YAG)

Solid-state lasers or laser amplifiers where the light is guided due to the total internal reflection in a single mode optical fiber are instead called **fiber lasers**

Gas lasers: Helium-Neon laser (HeNe), CO₂

Types of laser – Fiber laser

In fiber lasers, a rare-earth element such as ytterbium is doped into the core of an optical fiber

Laser emission is created within the fibers using a semiconductor diode as the light source and delivered through a flexible optical fiber cable.

Fiber lasers have a monolithic, entirely solid-state design that does not require mirrors or optics

Types of laser – disk laser

- ✓ **Thin-disk laser:** diode-pumped, solid-state lasers where the gain medium is a laser crystal
- ✓ Typically **Yb:YAG** (Ytterbium Yttrium Aluminum Garnet) formed not as a rod but as a very thin disk
- ✓ **Nd:YAG** is also used but has a shorter emission wavelength
- ✓ The thickness of the disk is usually much smaller than the laser beam's diameter

Advantages: ability to cool very efficiently

Power and pulse energy can be scaled to much higher values than rods, fibers or slabs

Easy to scale power (increasing the diameter of the pump area of the disk) - trade-off is decreasing beam quality

Types of laser – diode laser

- ✓ The diode laser is rapidly becoming an indispensable device in modern life
- ✓ It is present in the domestic CD player, in optical communications, laser printers, laser pointers etc.
- ✓ The attraction of diode lasers over all other types of laser - extreme compactness, and ease of operation

Nd (Neodymium):YAG (Yttrium Aluminium Garnet) LASER

Type	:	Doped Insulator Laser
Active Medium	:	Yttrium Aluminium Garnet
Active Centre	:	Neodymium
Pumping Method	:	Optical Pumping
Pumping Source	:	Xenon Flash Pump
Optical Resonator	:	Ends of rods silver coated Two mirrors partially and totally reflecting
Power Output	:	20 kW
Nature of Output	:	Pulsed
Wavelength Emitted	:	1.064 μm

Laser sources in welding

Typical commercial lasers for welding

1. **CO₂** Laser
2. **Nd³⁺:YAG** Lasers
 - ✓ **Lamp**-pumped
 - ✓ **LD**-pumped
3. **Disk** Laser
4. **Diode** Laser
5. **Fiber** Laser

CO₂ Laser: Characteristics

Wavelength 10.6 μm ; far-infrared ray

Laser Media CO₂–N₂–He mixed gas (gas)

Average 45 kW (maximum)

Power (CW) (Normal) 500 W – 10 kW

Merits Easier high power (efficiency: 10 – 20%)

LD: Laser Diode i.e. electrically pumped semiconductor laser

Laser sources in welding

ADVANTAGES	DISADVANTAGES
Excellent metallurgical properties can be established in the welds	Rapid cooling rate may cause cracking in some metals
The heat affected zone adjacent to the weld is very narrow	Maximum joint thickness that can be welded by laser beam is somewhat limited
Aspects ratio (i.e., depth to width ratios) of the order of 10:1 attainable in LBW	High reflectivity and high thermal conductivity of materials like Al and Cu alloy can affect the weldability with lasers
Focused laser light provides high energy density	Some weld-porosity and brittleness can be expected due to its rapid solidification characteristics
Laser welding can be used at room temperature	Laser tends to have fairly low energy conversion efficiency
No vacuum chamber or X-ray shielding is required	Joints must be accurately positioned laterally under the beam

Laser Beam Optics

Application: focus, modify and shape the laser beam

Laser beam has ideal Gaussian intensity profile (TEM_{00} mode)

Short focal length: Faster weld speed, Less heat input

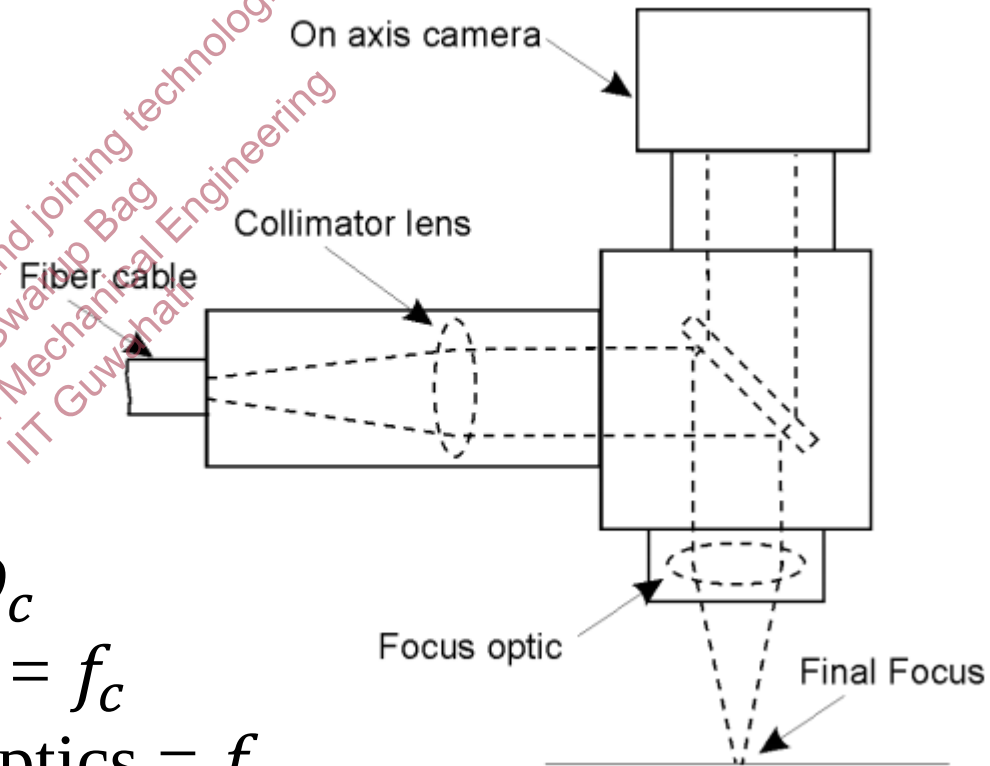
Long focal length: Longer depth of focus, Further from weld spatter & smoke

Core diameter of fiber = D_c

Focal length of collimator = f_c

Focal length of focusing optics = f_o

Final spot size $F_s = D_c \times \frac{f_c}{f_o}$



Laser Beam Optics

M^2 – deviation of laser beam from theoretical Gaussian

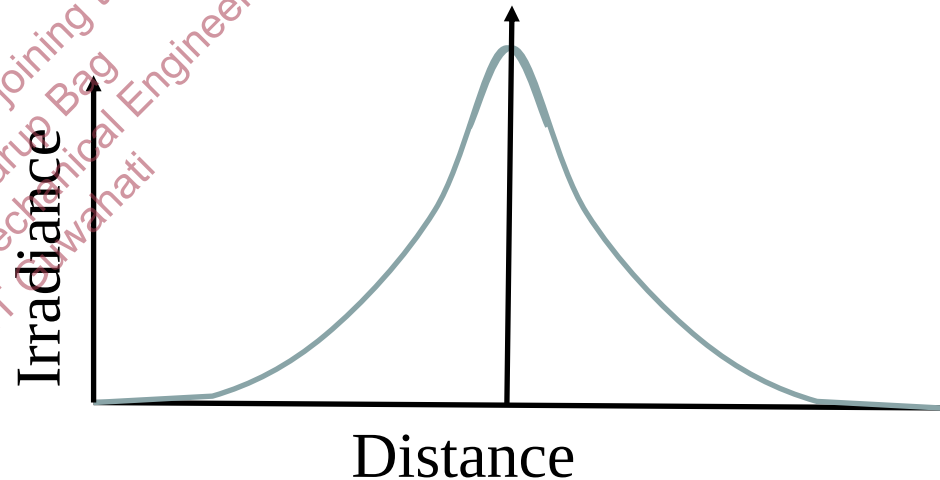
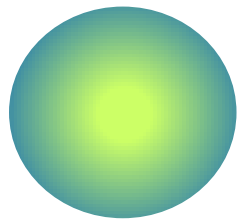
$M^2 = 1$ for theoretical Gaussian (TEM_{00} mode)

M^2 – between 1.1 to 1.7 for diode laser

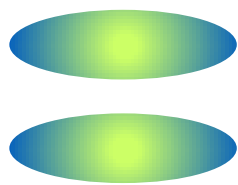
High energy multi-mode laser: M^2 can be as high as 25 or 30

Where wave front is flat –
beam waist radius w_0

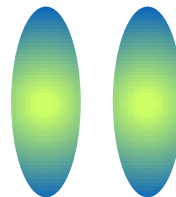
Laser Modes



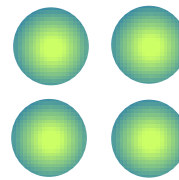
TEM_{00}



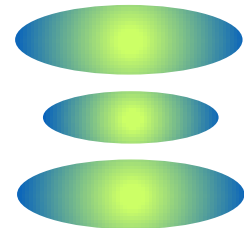
TEM_{01}



TEM_{10}



TEM_{11}

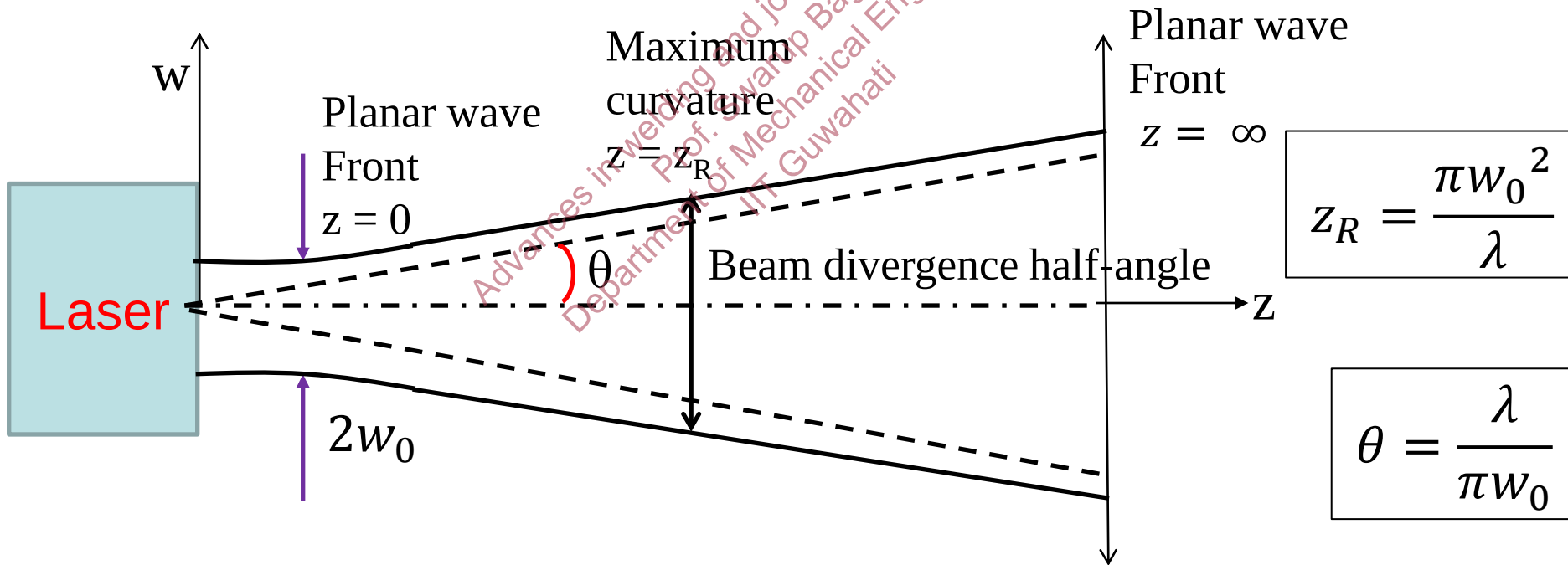


TEM_{02}

Laser Beam Optics

Where wave front is flat – beam waist radius w_0

Raleigh range: where the beam radius spreads by a factor $\sqrt{2}$ and wave front curvature is maximum



Laser Beam Optics

Beam parameter product (BPP) - of a laser beam is defined as the product of beam radius and the beam divergence half-angle

The usual units are mm mrad (millimeters times milliradians)

The BPP is often used to specify the beam quality of a laser beam

The higher the beam parameter product, the lower is the beam quality.

Example: Determine the diameter of focal spot for 10 mm focal length lens to focus the collimated output of a helium-neon laser (632.8 nm) that has a 1 mm diameter beam.

Assume divergence angle is small and laser is a point source

$$\theta \approx \frac{D}{2F}$$

D = diameter of the lens

F = focal length of the lens

Laser Beam Optics

Depth of focus is estimated at the point of maximum curvature
i.e. at z_R

$$\theta = \frac{\lambda}{\pi w_0}$$

$$z_R = \frac{\pi w_0^2}{\lambda}$$

$$\frac{D}{2F} = \frac{\lambda}{\pi w_0}$$

$$2w_0 = \frac{4\lambda F}{\pi D}$$

The diameter of the focal spot will be $2w_0$

Pulse characteristics

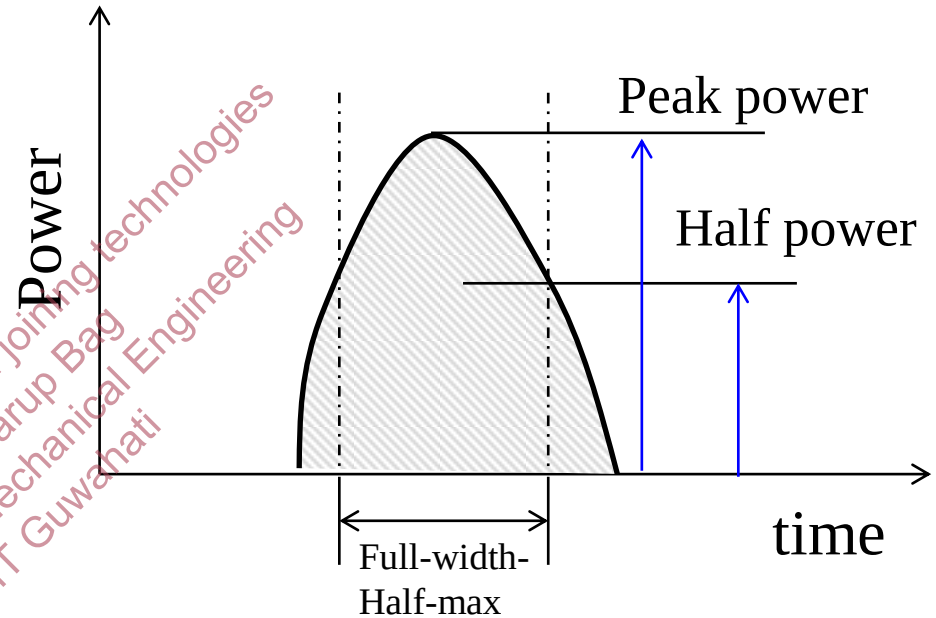
Parameters to be measured

- ✓ Average power (P_{av}) in 'W'
- ✓ Pulse repetition rate (R) in 'Hz' (pulse frequency)
- ✓ Pulse duration (t_{on}) in 's'

Area = pulse energy (E_p)

Energy per pulse: $E_p * R = P_{av}$

Peak power: $P_{max} * t_{on} = E_p$



Example: Pulse characteristics

Q 2.1: In a Nd:YAG laser, the measured parameters are: pulse frequency 10 kHz and average power 4 W. What is the pulse energy?

$$E_p * R = P_{av} \quad E_p = \frac{P_{av}}{R} = \frac{4}{10 \times 10^3} = 0.4 \text{ mJ}$$

Q. 2.2: In a Nd:YAG laser, the measured parameters are: pulse energy 5 mJ and pulse duration 10 μ s. What will be the peak power?

$$P_{max} * t_{on} = E_p \quad P_{max} = \frac{E_p}{t_{on}} = \frac{5 \times 10^{-3}}{10 \times 10^{-6}} = 500 \text{ W}$$

Process parameters for laser microwelding

- **Pulse energy**
- **Power density** →
- **M^2** → Measure of energy distribution
- **Pulse duration and frequency** →
- **Peak power** →
- **Spot size** →
- **Laser scanning speed** →

Measure of laser's capability

- ✓ Propagated with low divergence
- ✓ Focused to a small spot by lens

Beam quality measured by M^2 or BPP

- Ratio of divergence of actual beam to a theoretical diffraction limited beam
- M^2 tends to increase with increasing laser power

Primary Controllable Parameters

Laser beam energy output

Voltage and Pulse duration

Laser focus

Laser beam diameter

Increase voltage – deeper penetration with less melting

Increase pulse duration – deeper and wider melting

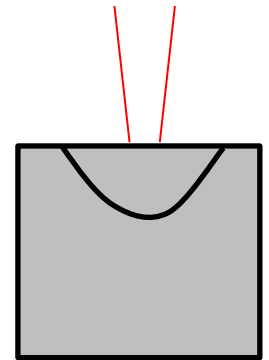
Increase beam diameter – shallow soft penetration and wide

Increase in voltage and pulse duration – deeper melting

Conduction mode and keyhole mode laser welding

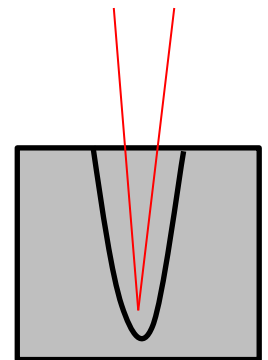
Conduction mode

- Power density less than 10^6 W/cm^2
- Heating the workpiece above the melting temperature without vaporizing
- The penetration is controlled by the conduction only



Keyhole mode

- Laser power density exceeding 10^6 W/cm^2
- Molten metal starts to vaporize
- opens up a blind hole (keyhole) in the molten metal
- Vapour pressure from the hot metal keeps the hole open during the weld
- Increase the energy efficiency of welding process due to multiple reflections of beam within cavity



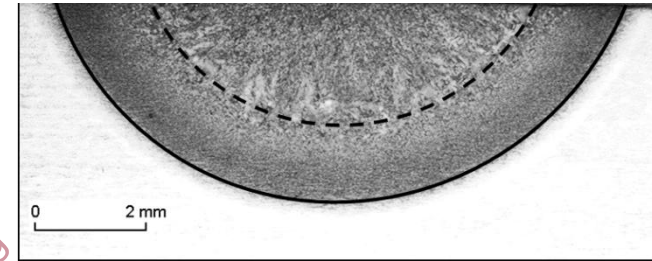
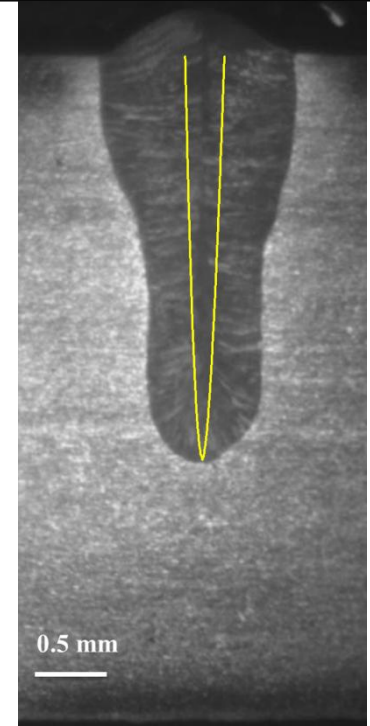
Conduction mode and keyhole mode laser welding

Conduction mode characteristics

- Low welding depth
- Small aspect ratio
- Low coupling efficiency
- Very smooth, highly aesthetic weld bead

Keyhole mode characteristics

- High welding depth
- High aspect ratio
- High coupling efficiency

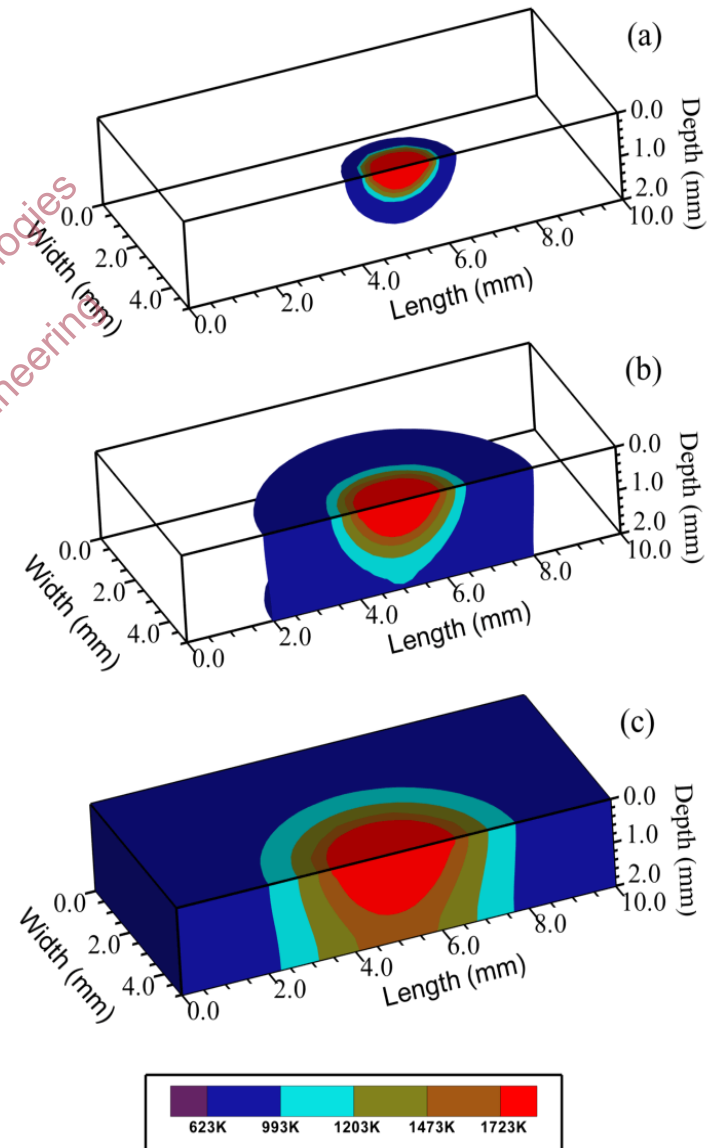


Conduction mode is normally used for welding of foils and thin sheets whereas keyhole mode is used for much thicker sections

Laser welding of metals

- Heat flux from heat source
- Localized melting and solidification
- Flow of molten metal
- Differential thermal expansion and contraction leading to distortion and residual stress

- Source of heat
- Fusion zone
- Heat affected Zone

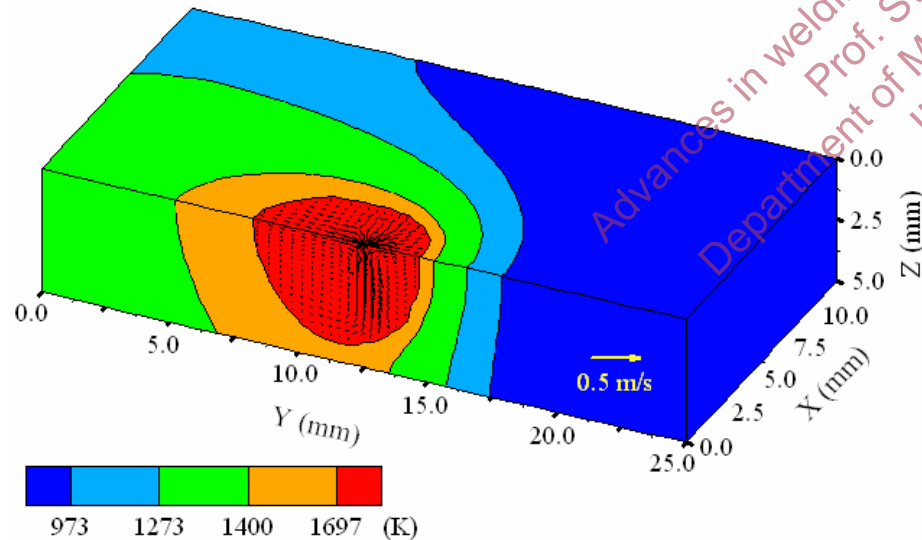
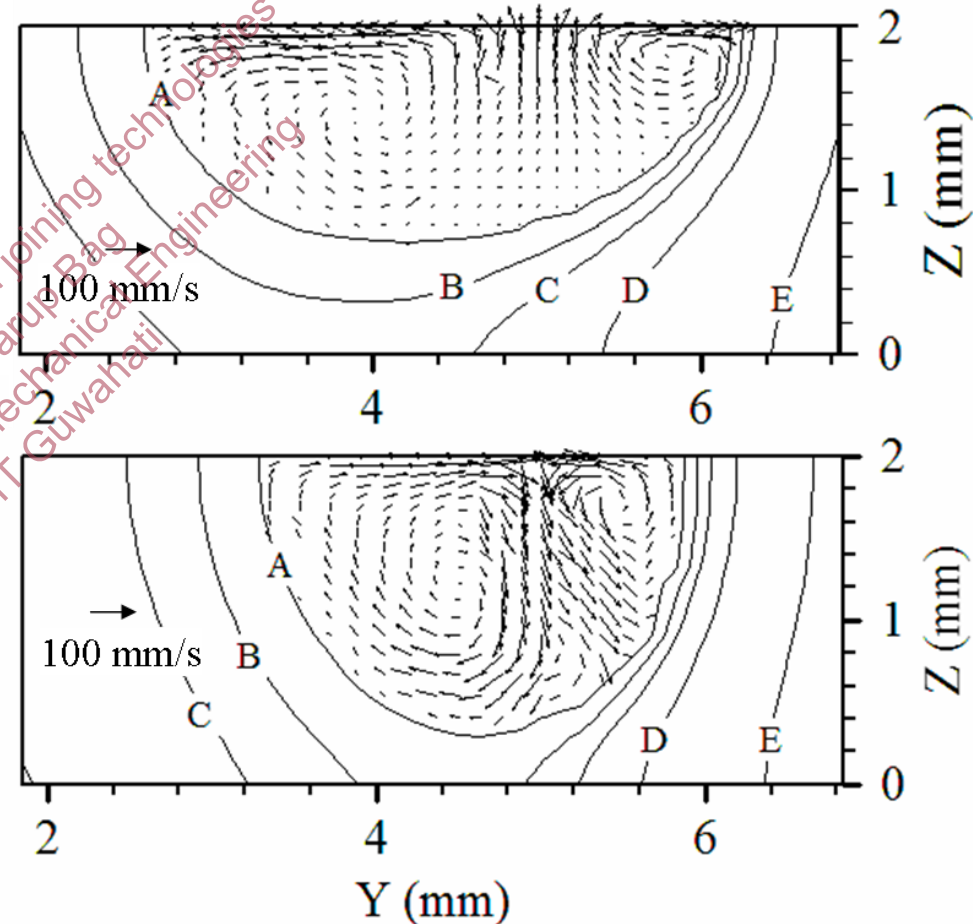


Laser welding of metals

Linear welding

Material flow

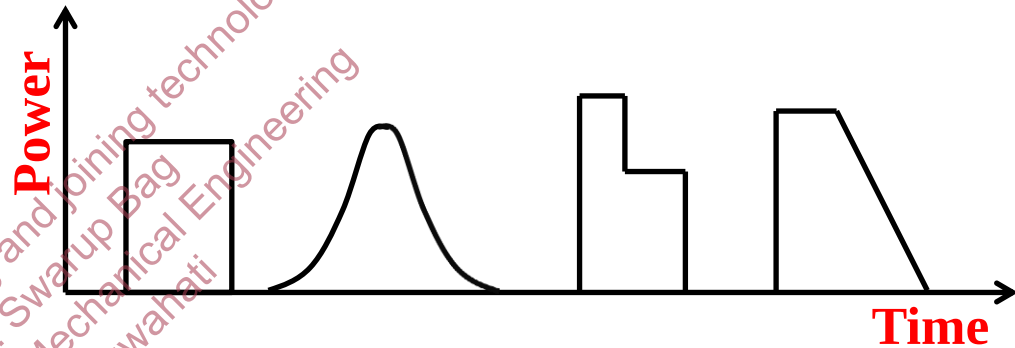
- Buoyancy force
- Surface tension force



Travel direction
→

Pulse shaping in laser welding

- Pulse shaping is advantageous than steady state pulse to overcome some inherent problems during joining of materials
- The instrumentation of pulse shaping over millisecond level is used for macro welding
- Temporally distribution of energy within a single laser pulse
- Modulation of suitable pulse shaping in time domain enables –
 - ✓ optimized penetration depth
 - ✓ welding of highly reflective materials
 - ✓ decides the mode i.e. keyhole or conduction mode welding
 - ✓ crack sensitive material

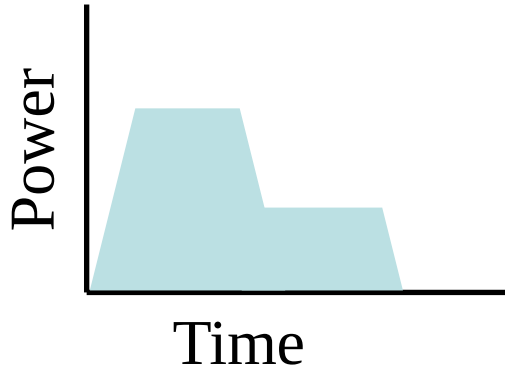


Phases of pulse shaping

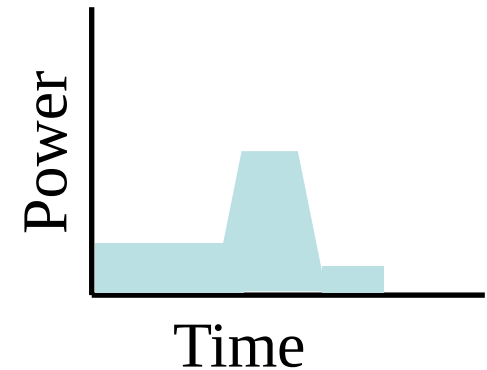
- initiation of melting
- starting to grow the melting
- initiation of welding between two materials
- stabilizing the weld between the materials
- cooling down of the weld

Pulse shaping in laser welding

Power is varied over pulse time



Upslope at beginning –
prevent thermal shock
Downslope at end –
controlled cooling



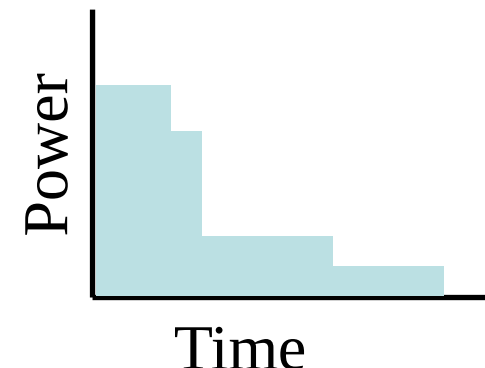
Large tolerance

Crack sensitive materials

Low peak power – melt first material and
then second material

Power reduced gradually – stable the melt
and cool down

High peak power – to start melting
Molten material – absorption rate increases
Reduce power – rapidly, not gradually

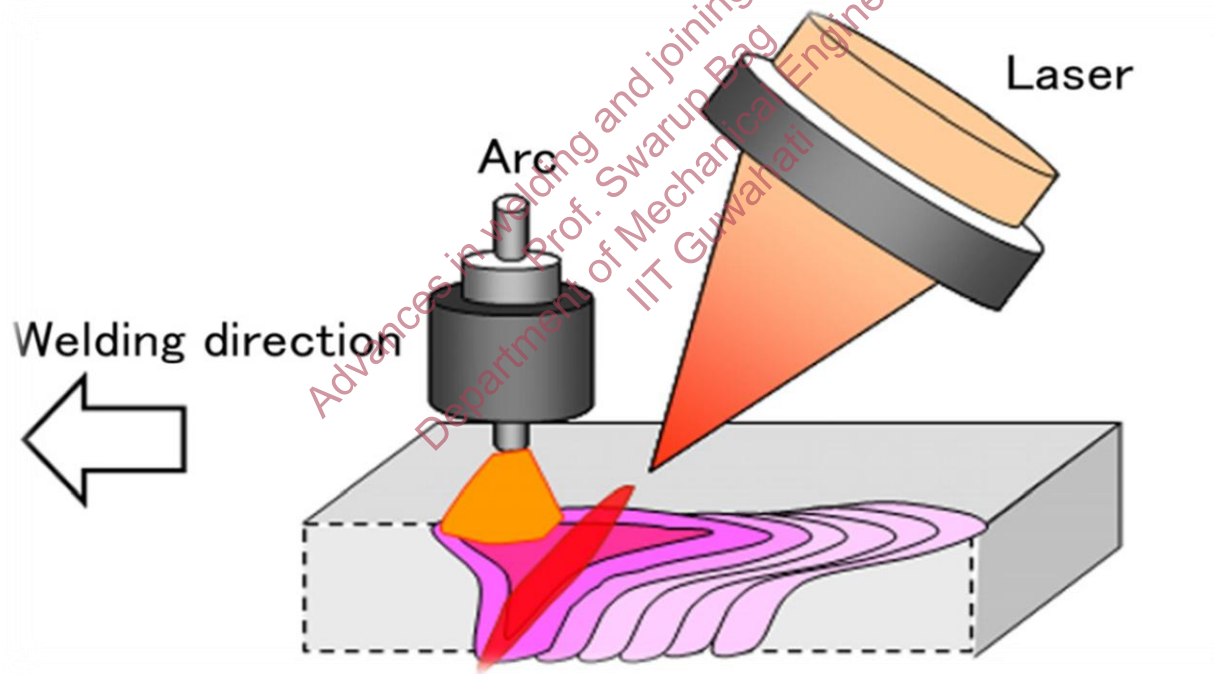


High reflective material

Laser-assisted Hybrid welding

- Hybrid welding involve use of laser in combination with a second energy source (arc welding)

Examples: laser with TIG, Laser with plasma, laser/MIG-MAG



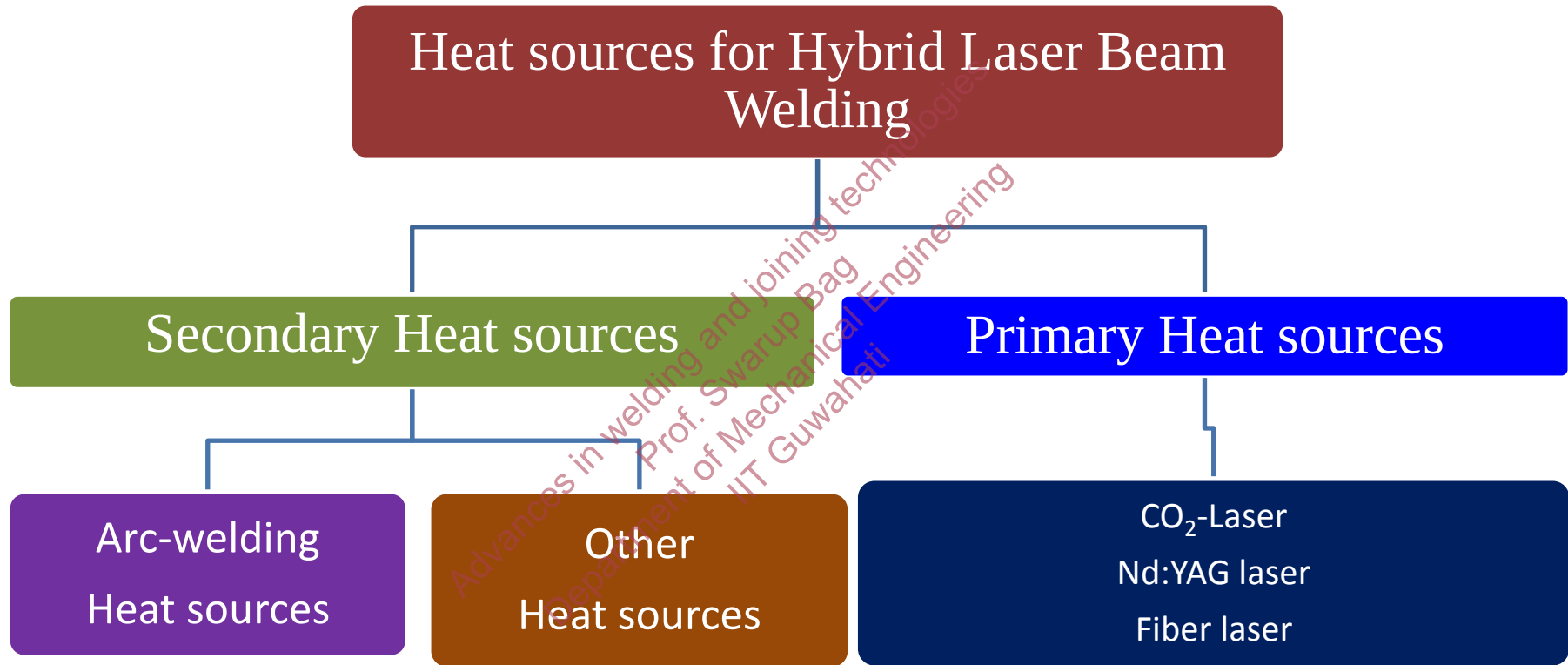
Laser-assisted Hybrid welding

Principle

- Combination of gas or solid state laser (CO_2 or Nd:YAG) and arc welding (GTAW, GMAW or PAW) processes supply energy to the work surface
- The focused laser beam impinges on the workpiece surface may cause **vaporization of the workpiece** material and formation of a deep vapor-filled capillary i.e. **keyhole**
- The power of the arc welding process introduces more energy to the zone of laser beam impingement causing the process **gas to be ionized, thus enhances arc stability**
- The hybrid process results in an increase in both **weld penetration and welding speed** as compared to each process individually
- The arc heats the metal and **helps the laser beam absorption for welding of highly reflective aluminium surface**

Laser-assisted Hybrid welding

Classification of Hybrid welding on the basis of selected heat source



Note: Hybrid laser brazing - use resistance heating between the part and the tip of the wire feeding system to increase the temperature of the wire.

The laser then is used to take the brazing alloy to a melting temperature while at the same time heating the substrate to a high enough temperature

Laser-assisted Hybrid welding

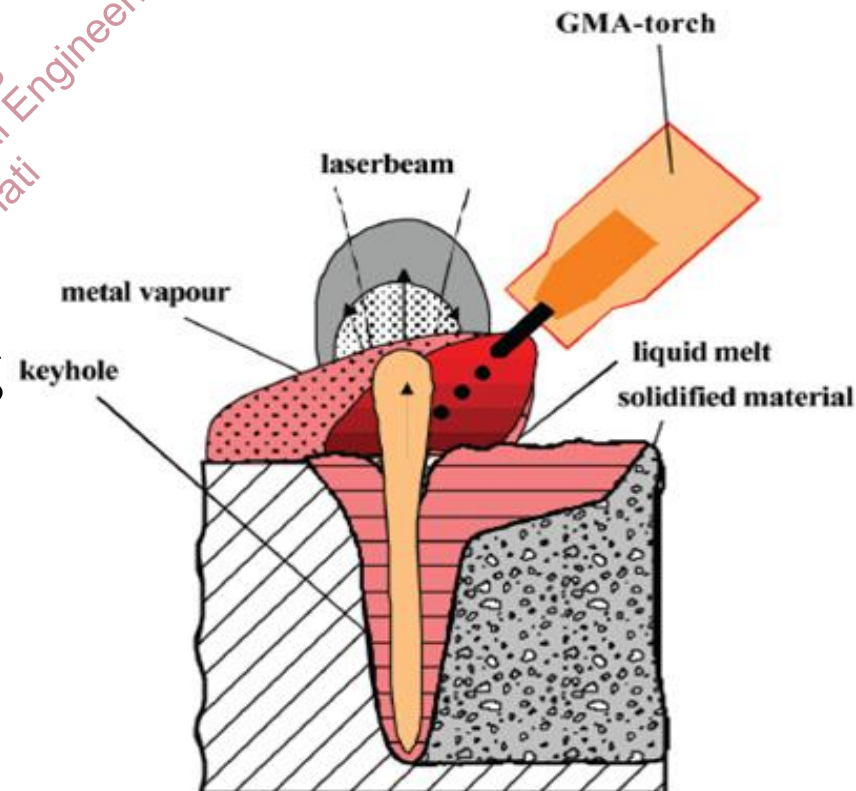
Overall benefits with respect to conventional welding process

- High efficiency process (around 80%)
- Ability to bridge relatively large gaps (of more than 0.5 mm)
- Slow cooling rates due to lower welding speed and higher heat input
- Welding of highly reflective materials is generally not difficult
- Metallurgy of weld can be adjusted and larger gap can be filled by adding filler material

Laser-assisted Hybrid welding

Factor affecting metallurgical structures and mechanical properties of weld in presence of material addition

- Arc plasma formation and its effect on metal transfer and weld pool dynamics
- Laser-induced plasma formation and laser-plasma interaction
- Recoil pressure and other possible mechanisms contributing formation and dynamics
- Plasma-filler metal-weld pool interaction



Laser-assisted Hybrid welding

Influences of Hybrid welding process parameters on bead shape

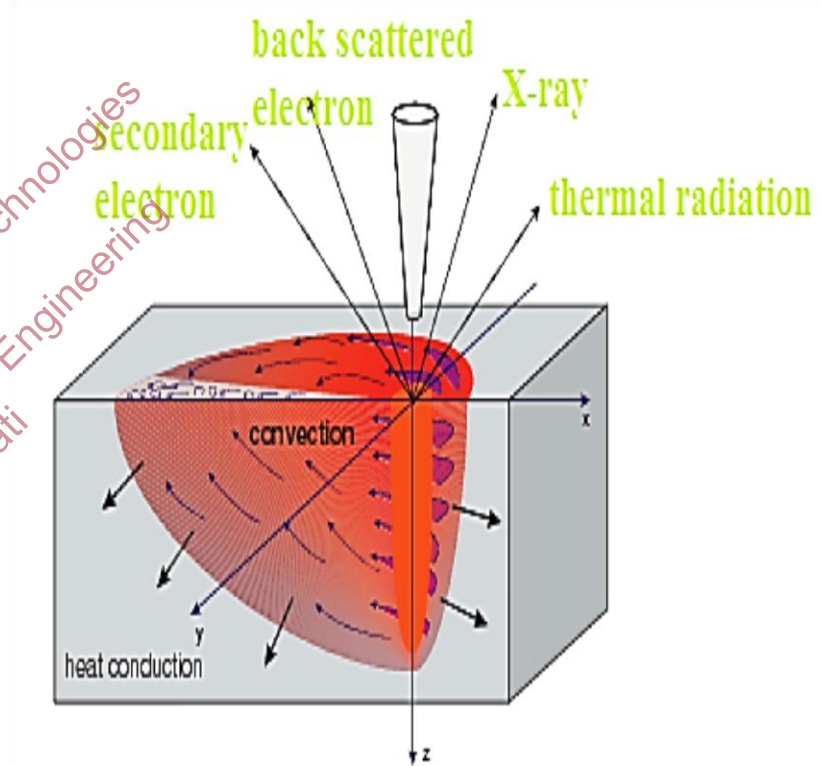
- Distance between arc and laser beam
smaller the distance, deeper penetration is achieved
- Pre and post position of laser beam
Laser beam precedes the arc was found to be superior since the assist gas flow does not affect the molten pool created by the arc
Shape of bead surface is disrupted by the assisted gas blowing into the molten pool
- Effect of arc power
at constant wire feed and laser power, increasing the arc power increases bead width

ELECTRON BEAM WELDING

Advances in welding and joining technologies
Prof. Sivapragasam Bag
Department of Mechanical Engineering
IIT Guwahati

Electron beam welding

- High energy density (up to 10^8 W/m²) fusion welding process
- Bombardment of intense beam of electrons on the target materials
- Instantaneous conversion of the kinetic energy into thermal energy
- Impingement of electrons causes weldment interface to melt and produces the weld-joint coalescence



Electron beam welding

- The electron beam gun has a tungsten filament which is heated, freeing electrons
- The electrons are accelerated from the source with high voltage potential between a cathode and anode
- The stream of electrons then pass through a hole in the anode. The beam is directed by magnetic forces of focusing and deflecting coils.
-
- This beam is directed out and strikes the workpiece
- The kinetic energy of the electrons is transferred to heat upon impact of the workpiece and cuts a perfect hole at the weld joint
- Molten metal fills in behind the beam, creating a deep finished weld

Electron beam welding

Advantages of Electron beam welding

- ✓ Maximum amount of weld penetration with the least amount of heat input reduces distortion
- ✓ Electron beam welding often reduces the need for secondary operations
- ✓ A cleaner, stronger and homogeneous weld is produced in a vacuum
- ✓ The electron beam machine's vacuum environment eliminates atmospheric contaminants in the weld
- ✓ Exotic alloys and dissimilar materials can be welded
- ✓ Extreme precision due to CNC reduces the scrap rate

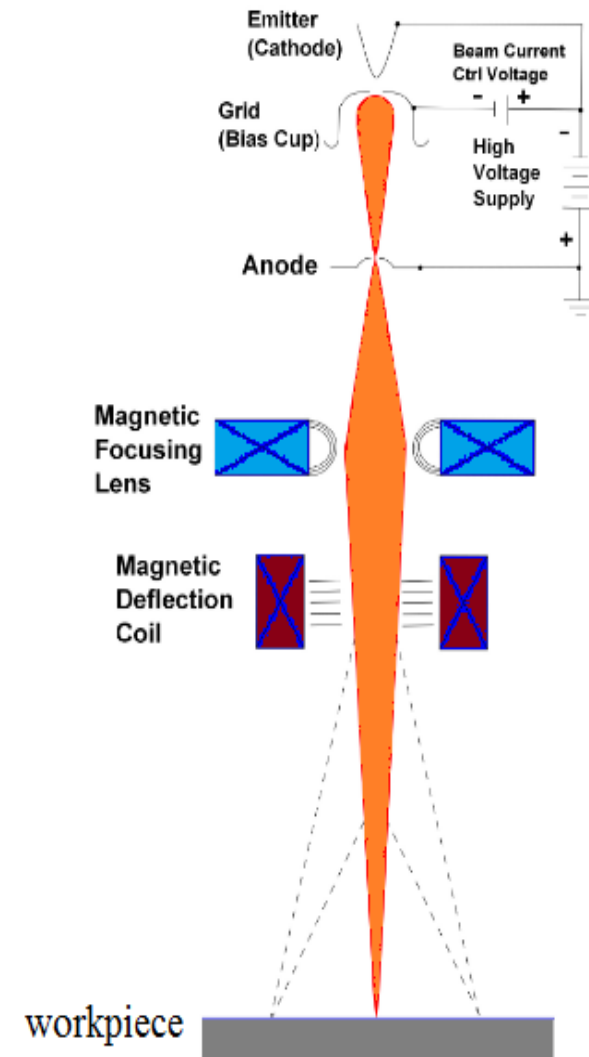
Typical applications of electron beam welding

- Bi-metal saw blades
- Transmission assemblies
- Aerospace components

Electron beam welding

Principle

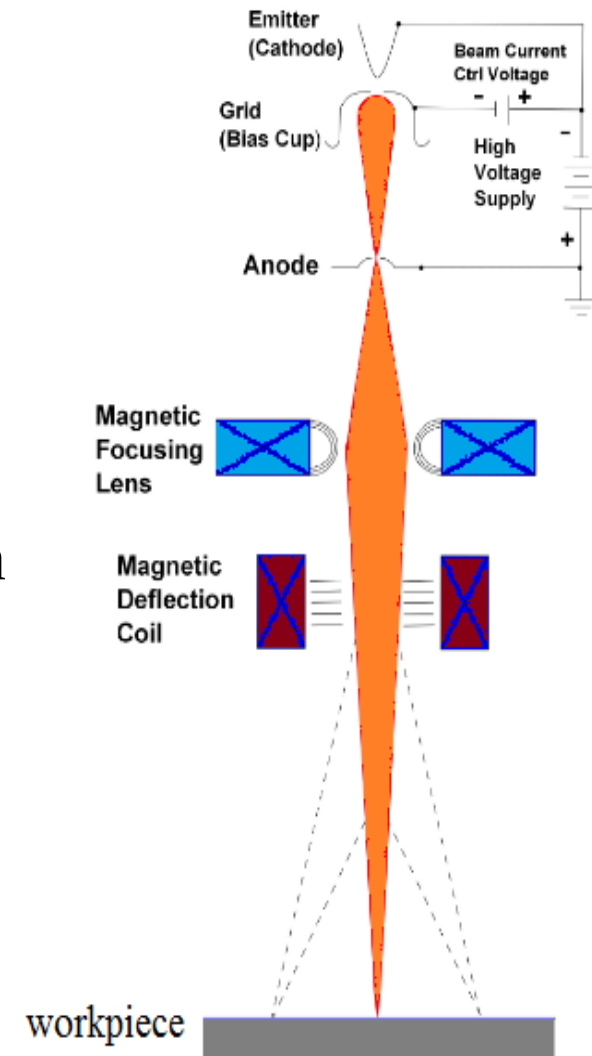
- The heart of the EBW process is the electron beam generation from the electron gun/column
- Electron are generated by heating a negatively-charged filament (cathode) to its **thermionic emission** temperature range, upon which electron are emitted
- Electrons are accelerated by electric field by negatively-charged bias electrode located between cathode and anode



Electron beam welding

Principle

- The electron beam can be focused under vacuum, and strikes the metal surface at velocities of up to 70% of the speed of light.
- About 95% of the electrons kinetic energy is converted into heat.
- The electron beam can be focused on diameter in the range of 0.3 - 0.8 mm
- One key feature is its ability to perform deep penetration welding with Keyhole mode



Keyhole formation mechanism

- The power density of these process is higher 10^9 W/m^2 .
- As a consequence of the high energy concentration, the mechanism of weld pool formation is somewhat different from the normal fusion welding process
- In joint area, material is heated to very high temperatures and may vaporize
- A deep crater or hole is formed immediately under heat source
- A reservoir of molten metal is produced behind this 'keyhole'
- As the heat source moves forward the hole is filled with molten metal from the reservoir
- This solidifies to form the weld bead. This technique is known as Keyhole formation

Forces in Keyhole formation

- The forces which create the keyhole in EBW are:
 - Electron momentum
 - Vapour pressure
 - Recoil pressure
- Surface tension and gravitational forces counteract keyhole formation but under normal circumstances, the keyhole-forming forces are much higher.
- The electron momentum pressure P_a is given as:

$$P_a = \frac{2Jm_eV}{e^2}$$

where, J = current density

V = accelerating voltage

m_e = electronic mass

Control parameters for EBW

- There is inter-relationship between power-travel speed and thickness
- Welding performance may be significantly changed by means of secondary controls
- Depth-to-width ratio can be controlled by beam focus and deflection

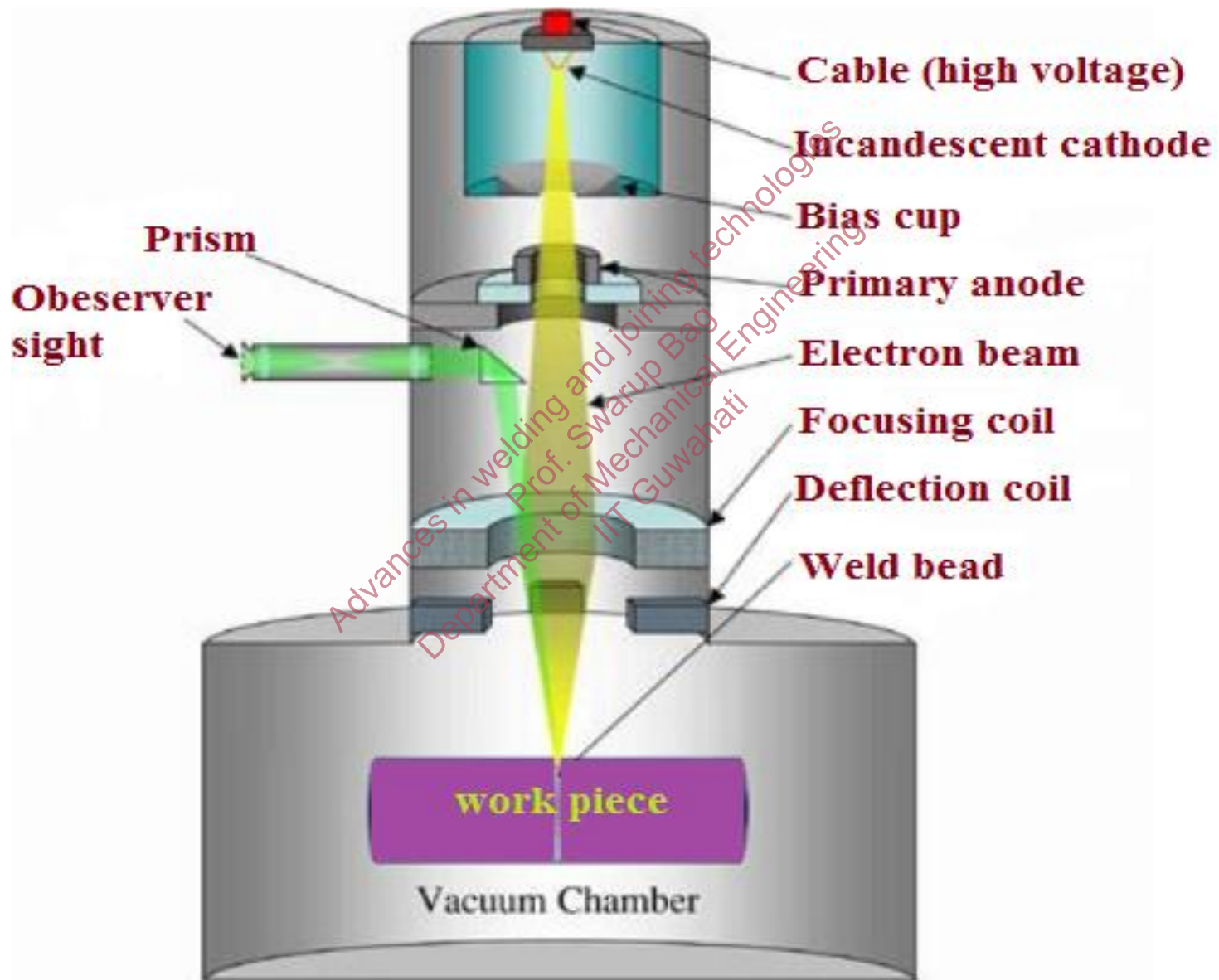
Primary Variables

- Filament current voltage
- Travel speed

Secondary Variables

- Beam focus
- Beam deflection
- Power supply
- Vacuum

Electron beam welding machine



Electron beam welding

Mechanical power of a beam of electrons

$$P_{\text{kinetic}} = \frac{E_{\text{kinetic}}}{t} = \frac{1}{2} (m_e \times n) \times v_e^2 \times \eta$$

where, $m_e = 9.109 \times 10^{-31} \text{ kg}$; $v_e < v_{\text{light}} = 3 \times 10^8 \text{ m/s}$

typically: $v_e = [0.3 \text{ to } 0.7] \times v_{\text{light}}$

n – number of electrons per unit of time

Heat input (energy input), J/mm

$$\text{Heat input} = \eta \frac{V \times I}{v}$$

where V = beam accelerating voltage (Volt)

I = beam current (A)

v = travel speed (m/s)

P = beam power - $V \times I$ (W or J/s)

η = fusion efficiency

Effect of EBM variable on bead geometry

Accelerating voltage: accelerating voltage is increased, the depth of penetration will also increase

Beam current: for any given accelerating voltage, the penetration will increase with beam current

Travel speed: the weld bead will become narrow and penetration will decrease as the travel speed is increased

Beam spot size: sharp focus of the beam will produce a narrow, parallel-sided weld geometry because the effective beam power density will be the maximum

Advantages of EBW

- Accurately controllable energy density and small beam size can weld thin and very thick metals (0.025 - 300 mm)
- Possible accurate beam alignment at any position allows the two base metals to melt selectively to better satisfy the metallurgical compatibilities
- Low total heat input produces narrow bead and HAZ as a result low residual stresses and minimum distortion
- It is possible to solve problems associated with metallurgical incompatibility more accurately with EBW when using a suitable filler material
- Vacuumed environment for welding minimizes surface contamination of the metal by O_2 , N_2 and H_2
- Dissimilar metal combination involving high thermal conductivity metals such as copper can be welded without preheating

Disadvantages of EBW

- Rapid solidification may result in brittleness of the weld and defects, e.g. porosity, crack etc.
- Use of vacuum chamber may reduce product size and limit the product design
- Possible beam deflection by electrostatic and magnetic fields due to dissimilar metal
- Electrical conductivity of materials is required
- High precision of seam preparation
- X-ray formation due to emission of secondary electrons from the workpiece
- Very high equipment cost

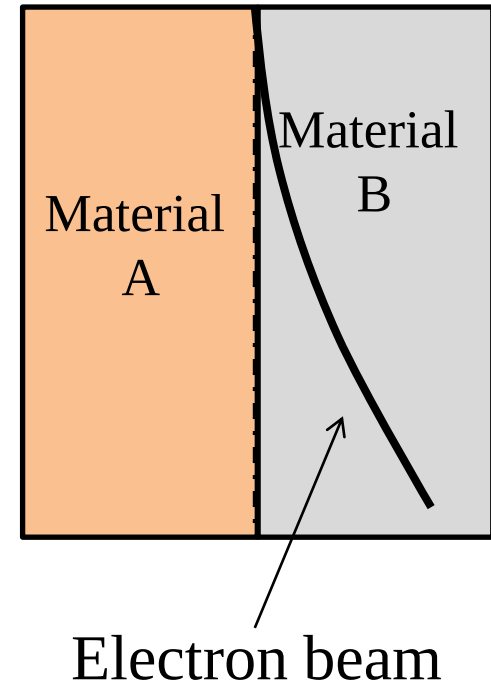
EBW of dissimilar materials

Deflection of beam

The **residual magnetism** of weldments in their fixtures (in ferromagnetic materials) because of contact with electromagnetics during welding

Thermo-electric magnetic fields caused by temperature gradients in dissimilar metals (Seebeck effect)

Electric currents on the wall of the vacuum chamber of an electron-beam welding unit (by interaction with eddy currents)



EBW of dissimilar materials

Three different sets of dissimilar metals namely

- (1) Iron and Copper
- (2) SS 304 and Low Carbon Steel
- (3) Low carbon Steel and Ni-Cu alloy

Seebeck effect

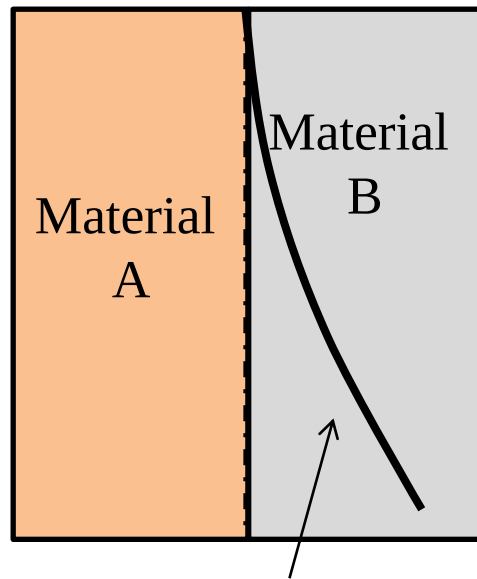
It is a phenomenon of producing of an electromotive force (emf) and consequently an electric current in a loop of material consisting of at least two dissimilar metals when two junctions are maintained at different temperatures.

Seebeck effect is the conversion of heat directly into electricity

$$E_{emf} = -S \nabla T$$

where S is the Seebeck coefficient and ∇T is the temperature gradient

EBW of dissimilar materials



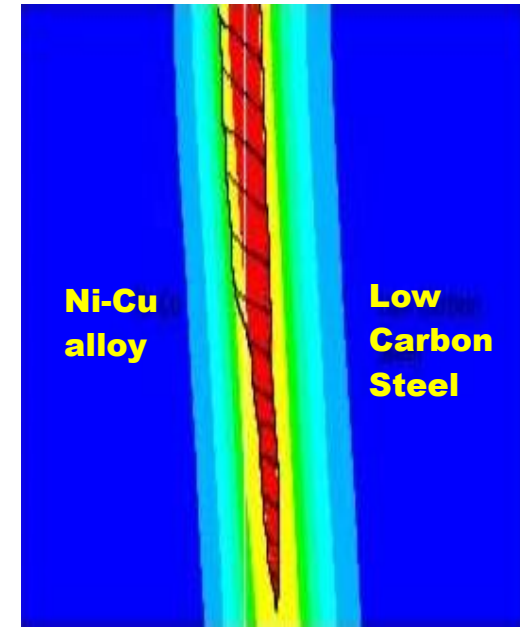
Electron beam

Higher seebeck emf:

Fe, low carbon steel, low carbon steel

Higher relative permeability:

Fe, low carbon steel, low carbon steel



SI No	Metals	Deflection angle (degree)	Deflected direction
1	Fe and Cu	2.86	Fe
2	SS304 and Low carbon steel	2.50	Low carbon steel
3	Low carbon steel and Ni-Cu alloy (7150)	8.51	Low carbon steel

Comparison between laser and electron beam welding

Perspective	Electron beam welding	Laser welding
Weld zone and HAZ	Narrow/smaller	Narrow/smaller
Penetration	Deep penetration	Lack penetration
Welding speed	Very high	high
Shielding gas	Not required	Nitrogen or argon shielding
Vacuum chamber	Required	Not required
Cost	Very high	Comparatively low
Generation of X-ray	Possible	Not-possible
Power efficiency	80-90%	10-20%
Size of work piece	Limited due to vacuum chamber	Not limited

**Thank you
for your kind attention**

End of Module 2

Laser and Electron Beam Welding

Advances in welding and joining technologies
Prof. Swarup Bag
Department of Mechanical Engineering
IIT Guwahati