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CUAW_o2 Advanced welding Process

A) Laser Beam Welding

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CENTER FOR DEFENCE, SPACE & SECURITY



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Learning outcomes



After this module, you will be able to:

1. Understand the basic concept of welding, classification of welding
2. Basic principle of laser welding, laser welding equipment, typical defect formation during welding.
3. Different modes of laser welding, heat transfer and fluid flow during welding, laser welding process parameters.
4. Methods for laser welding on-line monitoring and control.

Topics to be covered



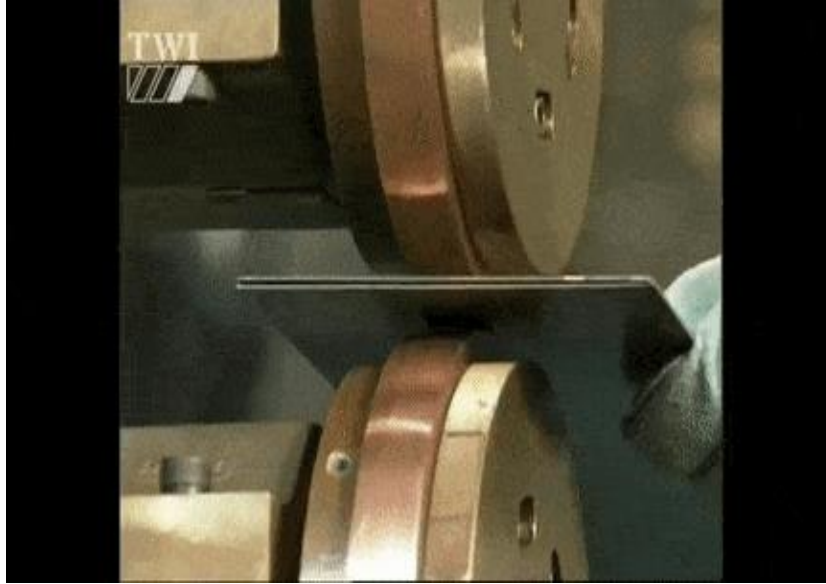
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- ☐ Importance and applications of Welding
- ☐ Different types of Welding
- ☐ Fundamentals of Laser
- ☐ Laser welding set up
- ☐ Modes of Laser Welding
- ☐ Advantages and Disadvantages

Introduction: Why, What and How Welding?



Welding is a consolidation process whereby two or more parts (similar/dissimilar) are fused together by means of heat, pressure or both forming a joint.



MakeAGIF.com

<https://www.westermans.com/blog/a-comprehensive-guide-to-spot-welding-how-does-it-work-and-what-is-it-used-for/>

<https://www.agerawelder.com/news/what-is-seam-welding/>

Importance of Welding



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Welding is a consolidation process whereby two or more parts (similar/dissimilar) are fused together by means of heat, pressure or both forming a joint.

- ☐ **Permanent Bonding of Materials**
- ☐ **Strength and Durability**
- ☐ **Versatility of Applications**
- ☐ **Design Flexibility**
- ☐ **Automatability and Efficiency**
- ☐ **Critical for Repair and Maintenance**

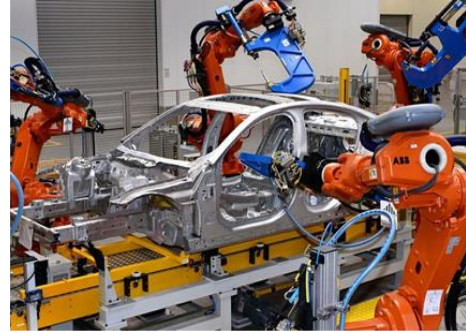
Applications of Welding



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Aerospace Sectors



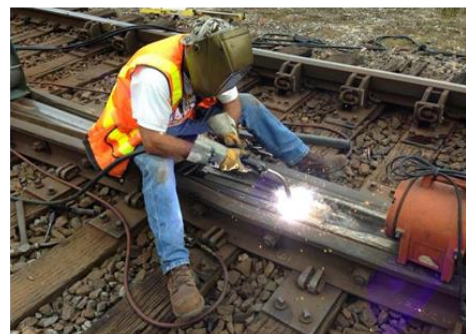
Automotive sectors



Construction &
infrastructure sectors



Manufacturing sectors



Railroads sectors



Shipping sectors

<https://www.themanufacturer.com/articles/sector-focus-aerospace-facing-headwinds-but-the-horizon-looks-clear/>

<https://wda-automotive.com/the-future-of-the-automotive-industry/>

<https://www.newcivilengineer.com/latest/confidence-among-uk-rail-supply-sector-remains-low-as-business-expected-to-slow-07-11-2024/>

Welding: Welding Positions & Design



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Designs

Positions

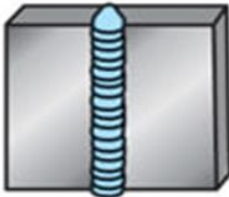
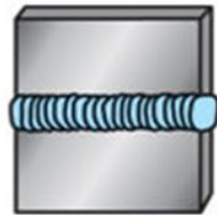
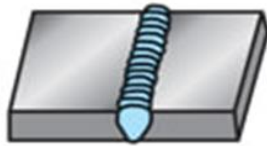
Flat

Horizontal

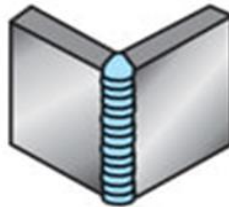
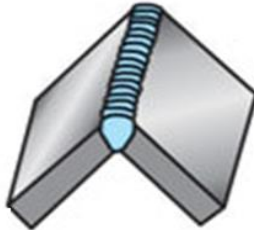
Vertical

Overhead

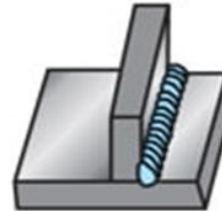
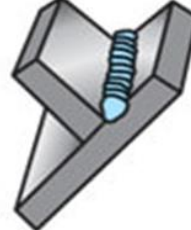
Butt Joint



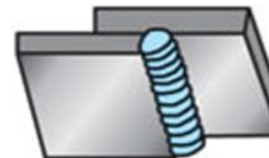
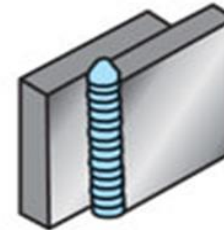
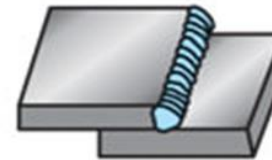
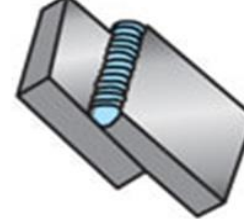
Corner Joint



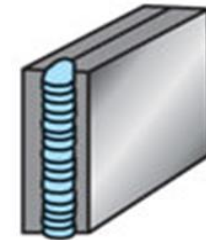
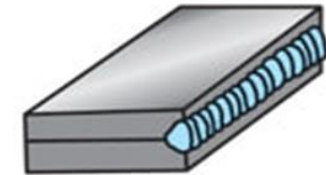
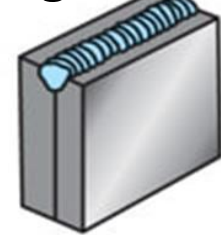
T-Joint



Lap Joint



Edge Joint





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Welding: Process parameters

1. Temperature

2. Pressure

3. Shielding [From air to prevent oxide, nitrides or other compounds formation]:

Flux: Chemical substance (CaCO_3 , SiO_2 , MnO , CaF_2). It also stabilize the arc and reduce spattering.

Vacuum: A space without matter.

Inert gas: Not combine chemically with the base metal or filler metal.

4. Filler materials: Is also melted and mixed with the material being welded.

➤ Covered electrodes

➤ Tubular electrode wires

➤ Bare electrode wires

➤ Welding fluxes

Welding: Classifications



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Fusion Welding

- Use heat to cause localized melt the base metals.
- Filler metal may or may not use.

Solid-State Welding

- Uses heat and pressure or pressure alone.
- Temperature does not reach the melting point

Brazing and Soldering

Welding: Classifications



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Brazing and Soldering

- **Brazing:** bronze, brass, Co, Au, Ni, Ag-alloy.
- **Soldering:** Pb-Sn alloy, Cu, Sn, Ag.

Welding: Classifications



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Brazing and Soldering

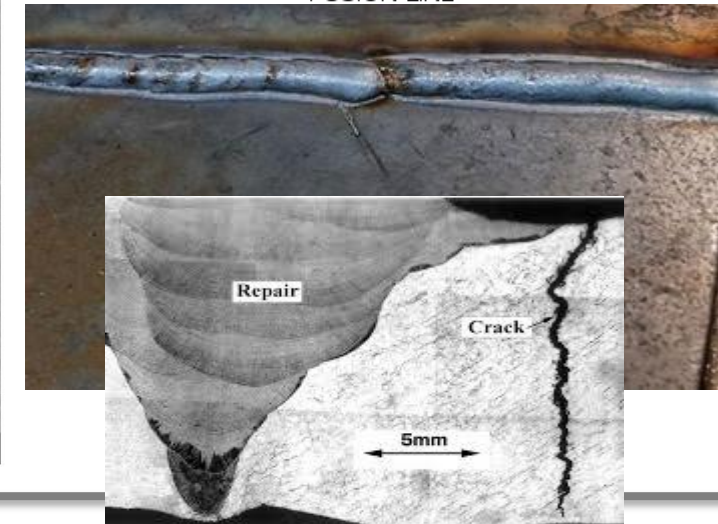
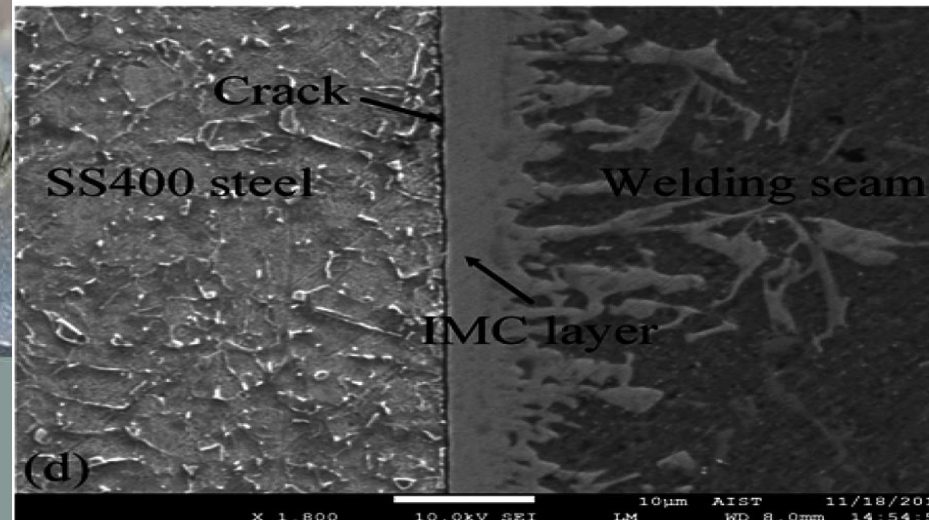
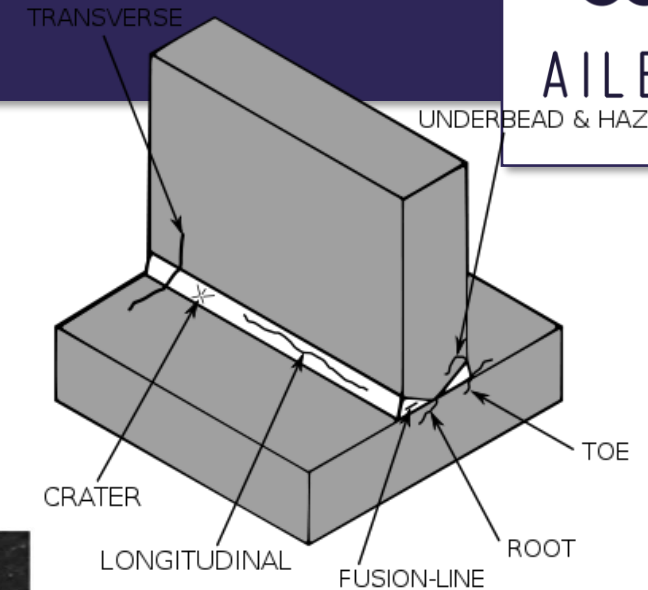
- Brazing: bronze, brass, Co, Au, Ni, Ag-alloy.
- **Soldering: Pb-Sn alloy, Cu, Sn, Ag.**

Weld defect: Types

1. Cracks: Fractures in the weld itself or in the metal adjacent to it.

2. Solid inclusions/compounds

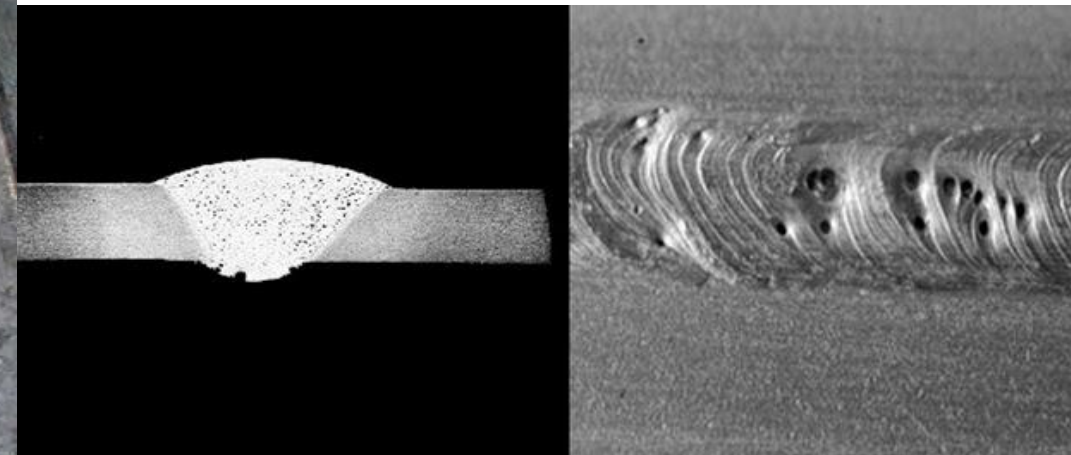
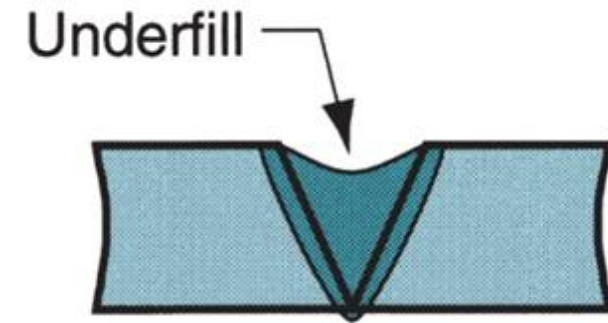
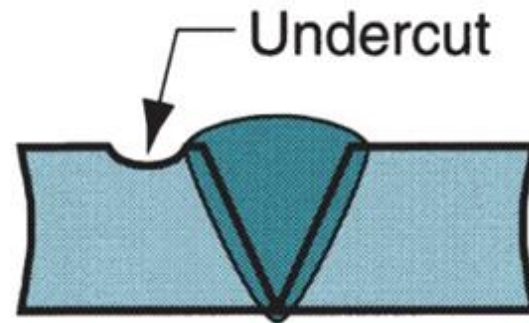
Nonmetallic solid material embedded in the weld formed by the reactions of fluxes/new phase formation.



Weld defect: Types

3. Cavities

Undercut, underfill, incomplete fusion, Porosity and shrinkage voids etc.



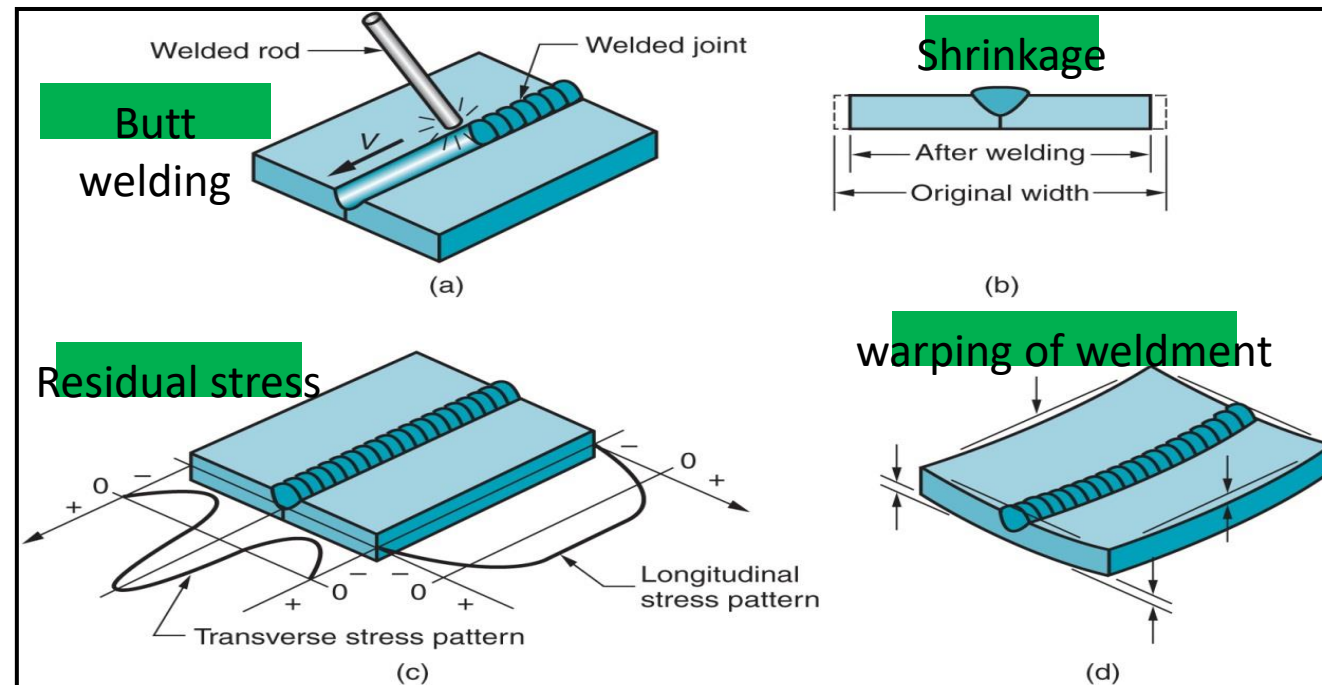


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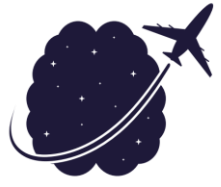
Weld defect: Types

4. Distortions & Stresses

Principle: Rapid heating and cooling in localized regions during fusion welding, results in thermal expansion and contraction that cause residual stresses, and stresses cause distortion and warpage.



<https://link.springer.com/article/10.1007/s40194-019-00816-y>



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Pros and Cons of Welding Joints

- ✓ Permanent joints.
- ✓ 100 % strength.
- ✓ No change in cross-sectional area
- ✓ Possibility to alter joint properties
- ✓ Various shapes can be joined.
- ✓ Dissimilar joining possible
- ✓ Plastics can also be joined.
- ✗ Change of Metallurgical properties.
- ✗ Presence of Heat affected region.
- ✗ Residual stresses generation.
- ✗ Distortion.
- ✗ Poor performance under vibration.
- ✗ Cracks formed due to heating and cooling.

Welding Classification: Energy source

Welding
Processes

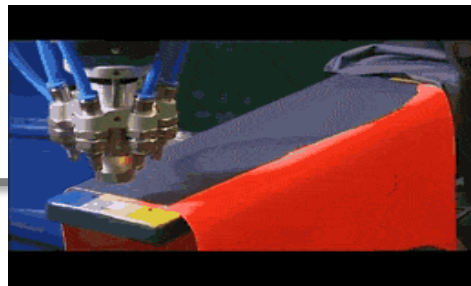
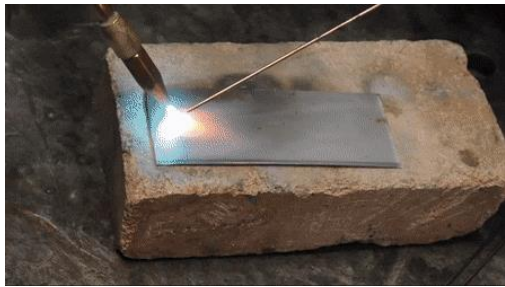
Oxyfuel Gas
Welding

Resistance
Welding

ARC Welding

High Energy
Beam Welding

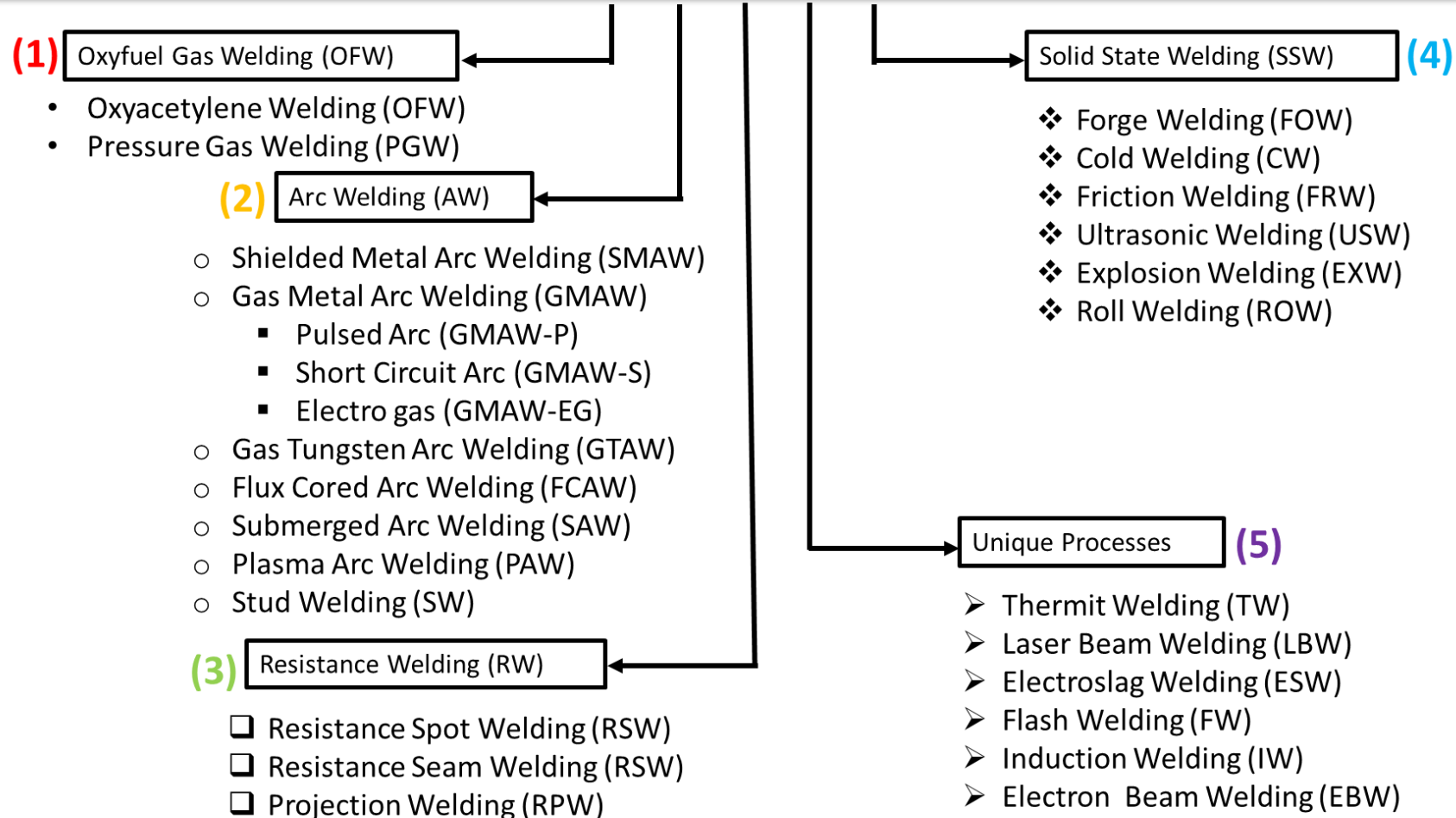
Solid State
Welding



Welding Classification: Energy source



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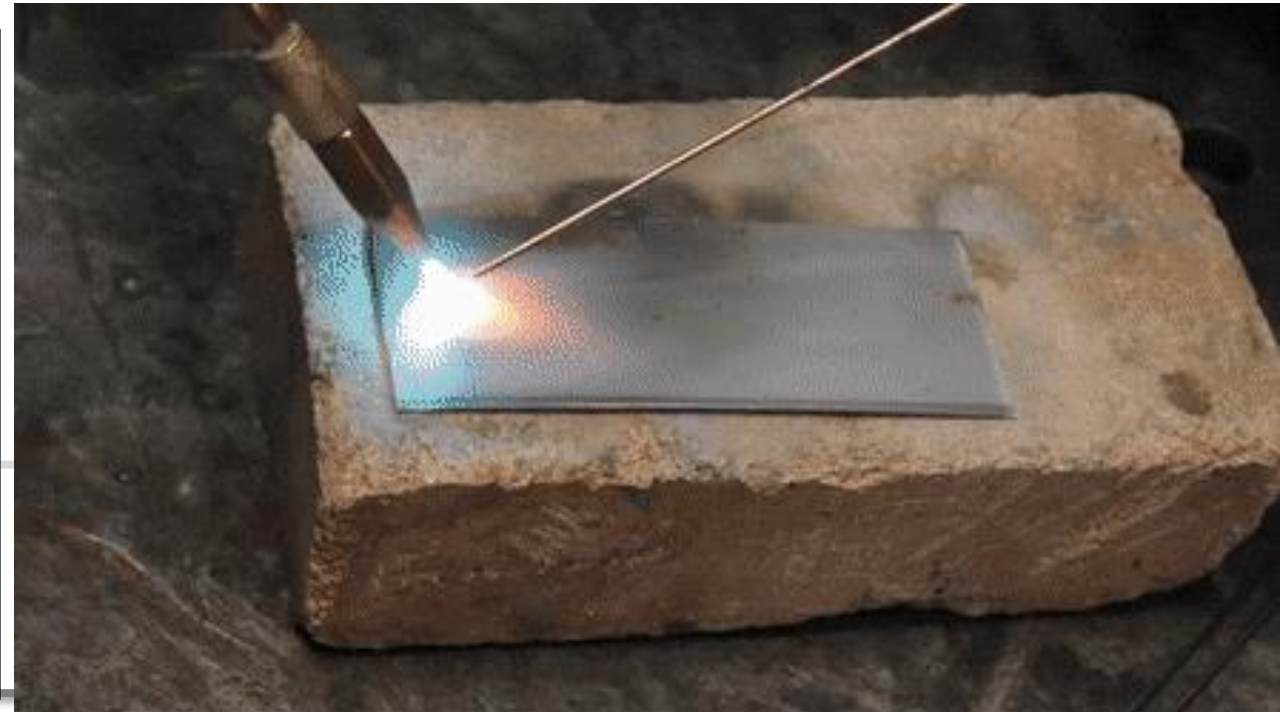
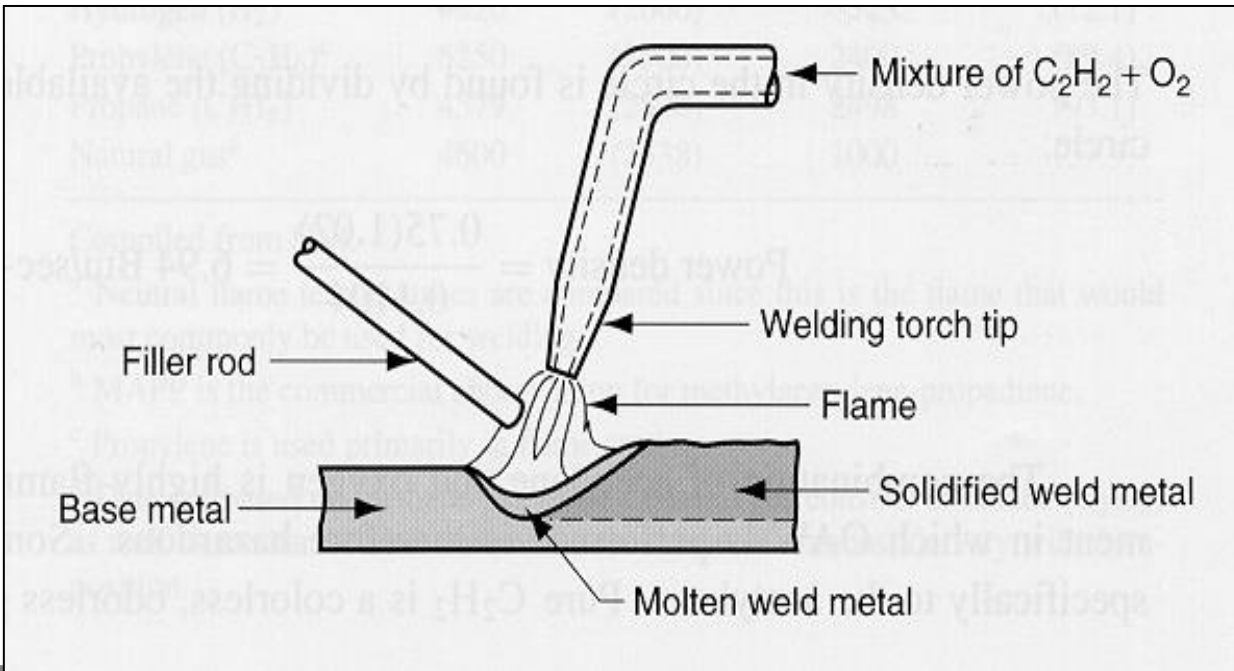


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Welding Classification: Energy source

(1) Oxyfuel Gas Welding (OFW)

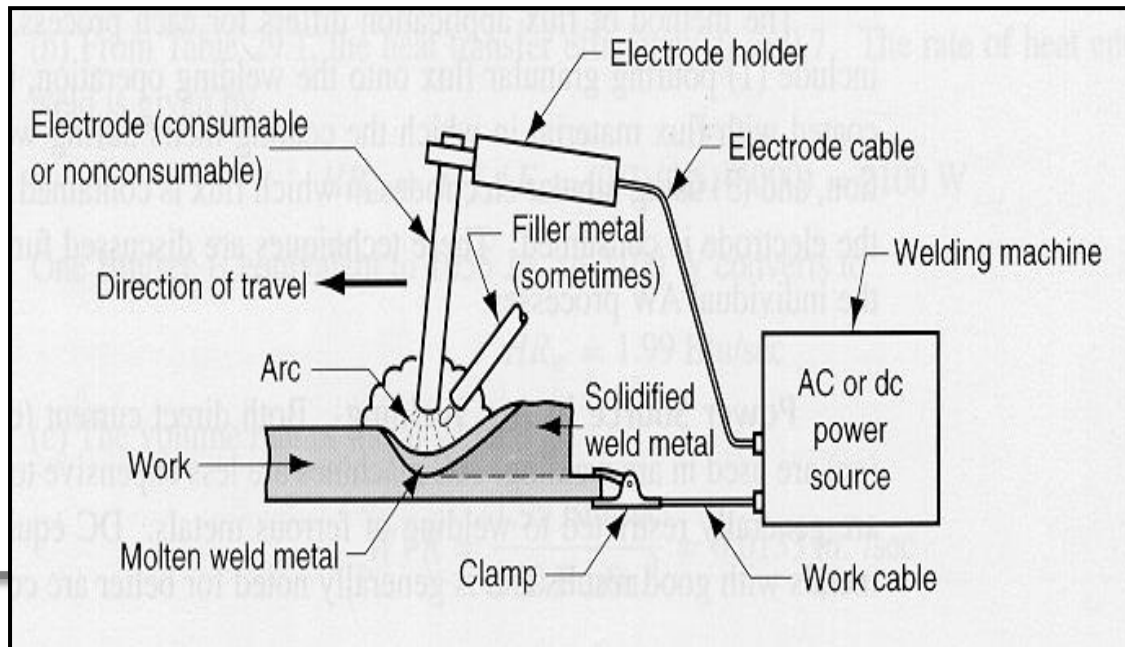
- Uses a high-temperature flame from the combustion of oxygen, acetylene and hydrogen.
- **Filler materials:** may or may not be used.



Welding Classification: Energy source

(2) Arc Welding (AW)

- An electric arc (DC/AC) to heat and melt the metals and solidifies to join the pieces together.
- **Electrodes:** consumable / non-consumable types.
- **Filler materials:** may/may not. Shielding gas, vapour & slag protect the welds & strengthen it.



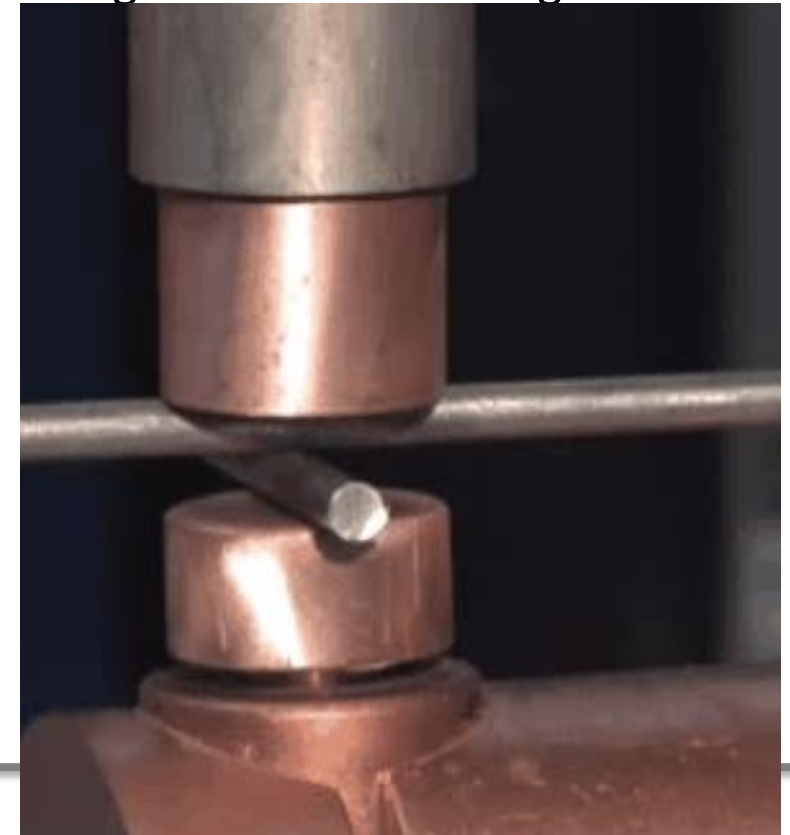
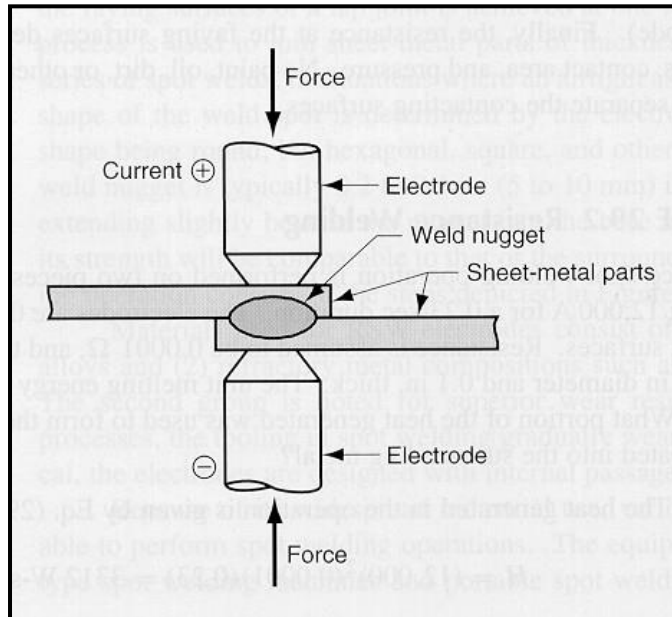
Welding Classification: Energy source



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Resistance Welding (RW)

- Heat and pressure to join metals by melting it by applying current using electrodes through the contact resistance between metal surfaces.
- Localized melting which forms weld nugget.



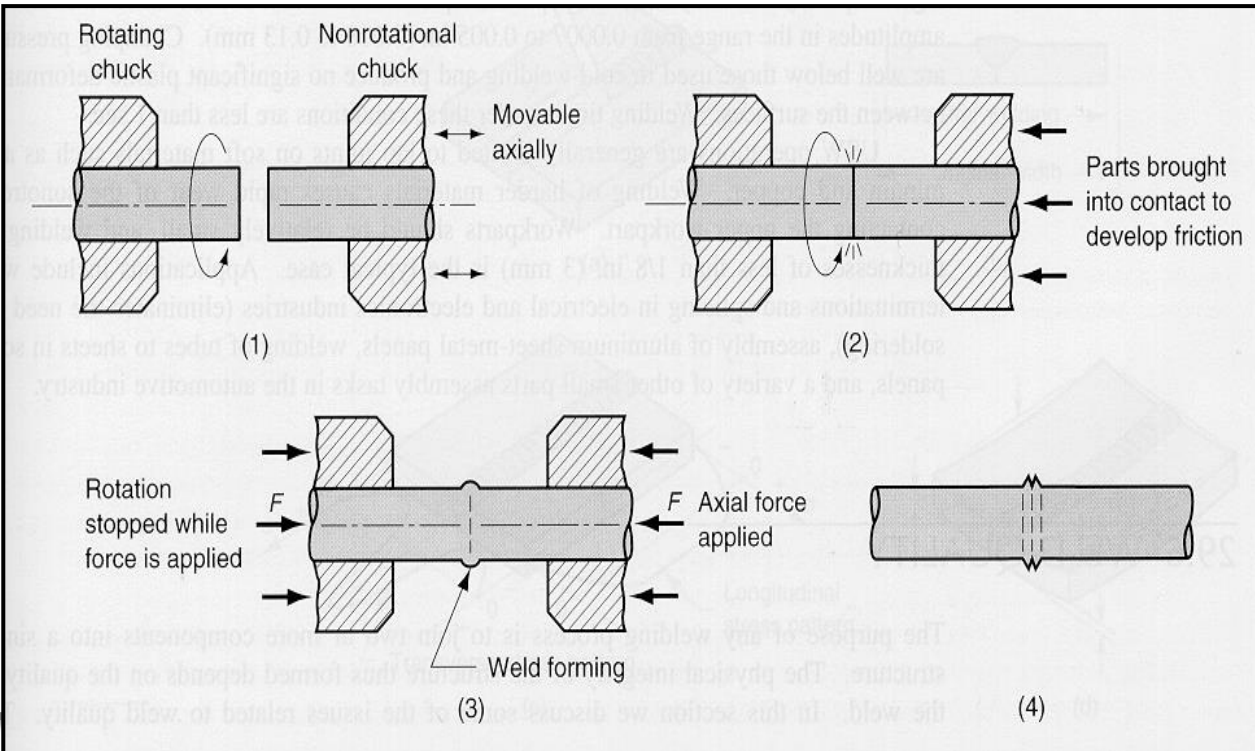
Welding Classification: Energy source



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Solid State Welding (SSW)

- Coalescence of materials without any filler materials.
- Pressure, friction, vibration and heat needed to join the metals by solid-state diffusion.

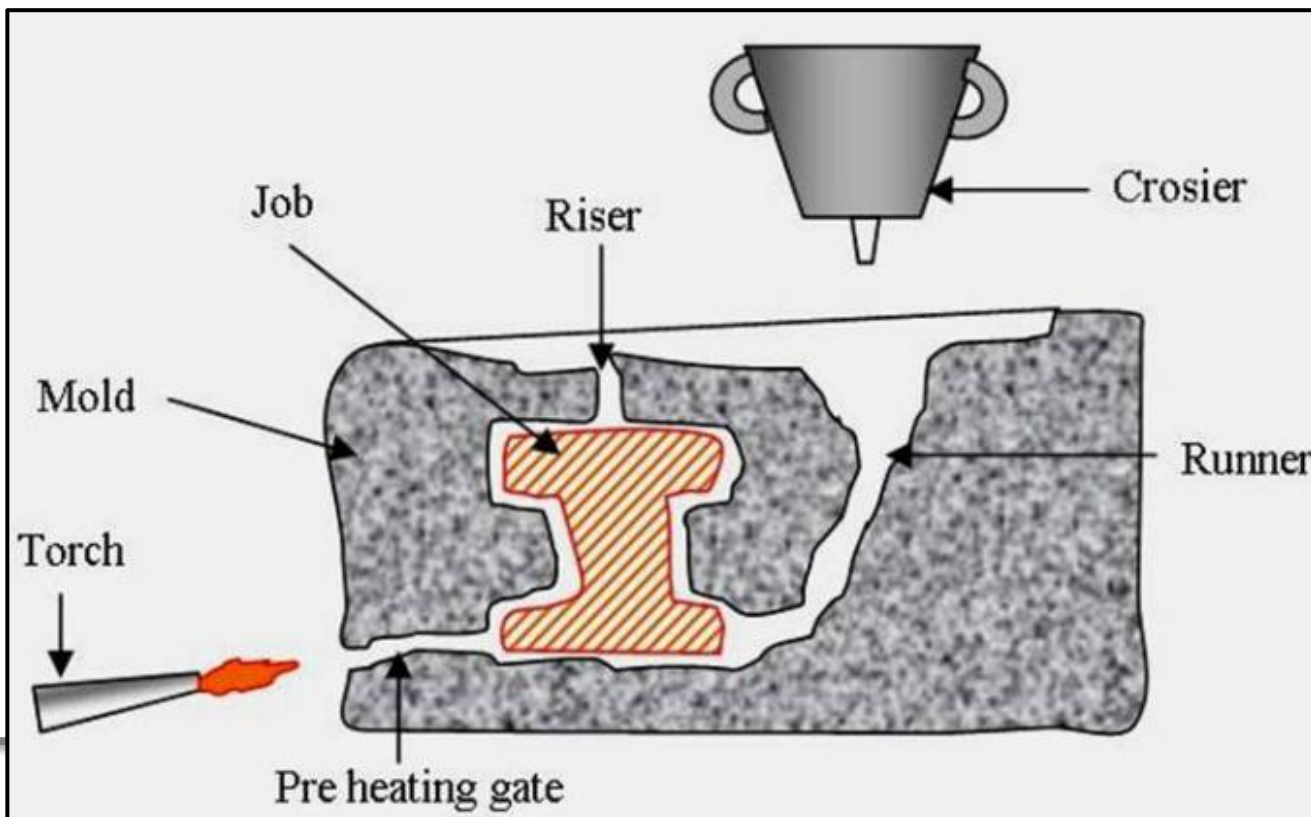


Welding Classification: Energy source



➤ **Thermit Welding (TW)**

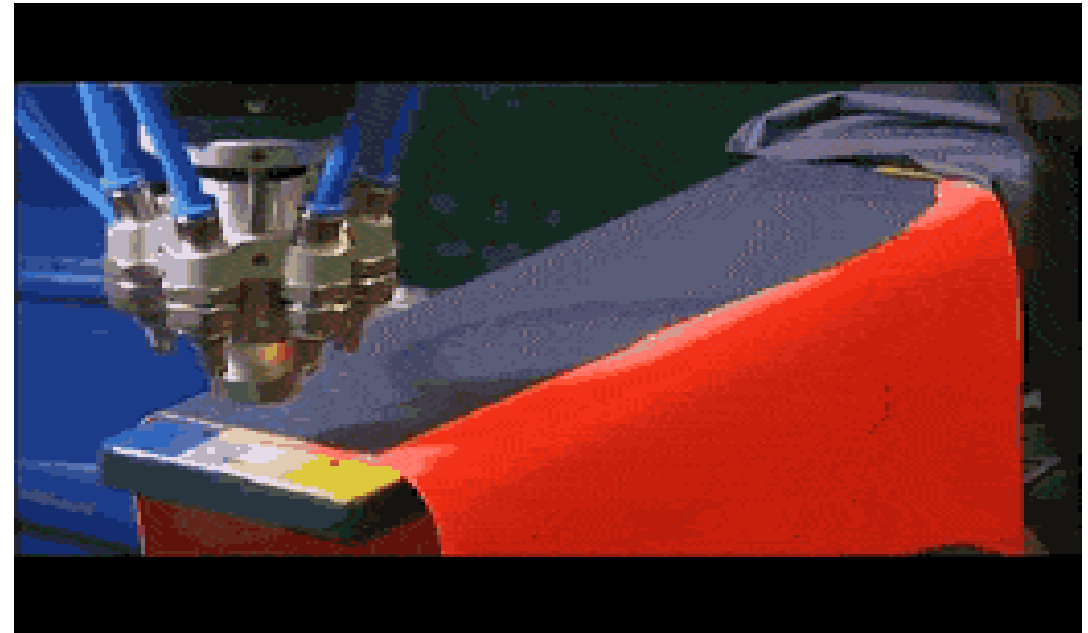
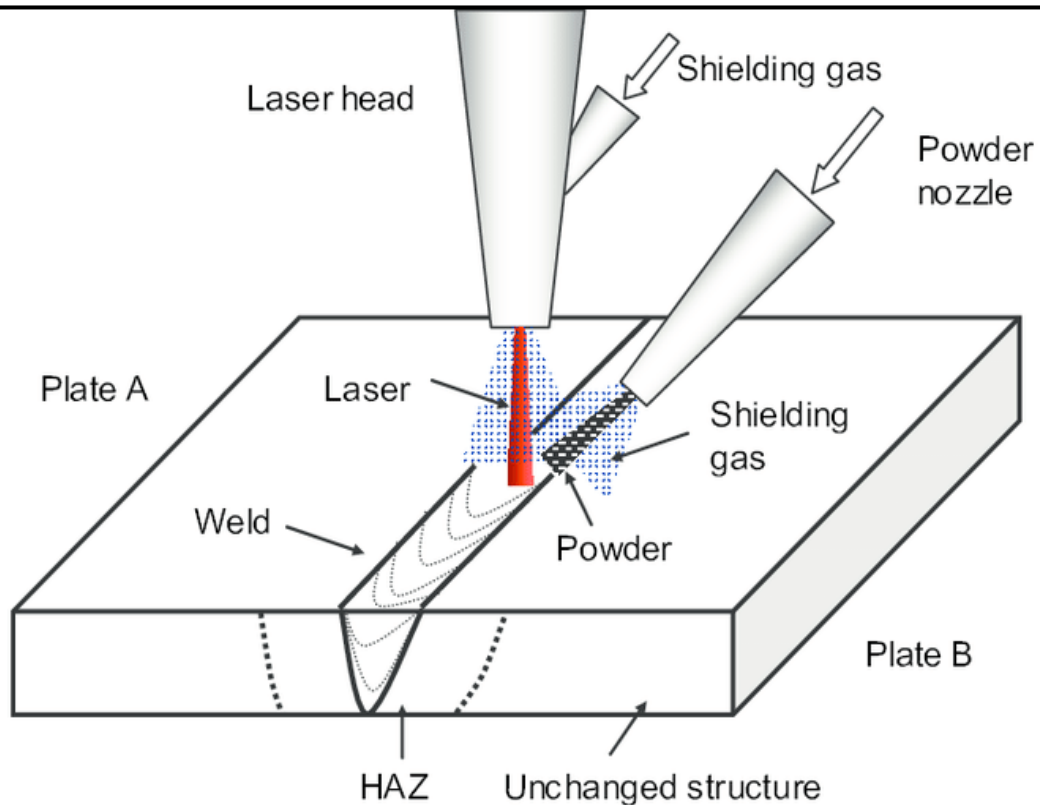
- Uses heat from an exothermic reaction ($\text{Al}:\text{Fe}_3\text{O}_4=1:3$) to produce coalescence between metals.



Welding Classification: Energy source

➤ Laser Beam Welding (LBW)

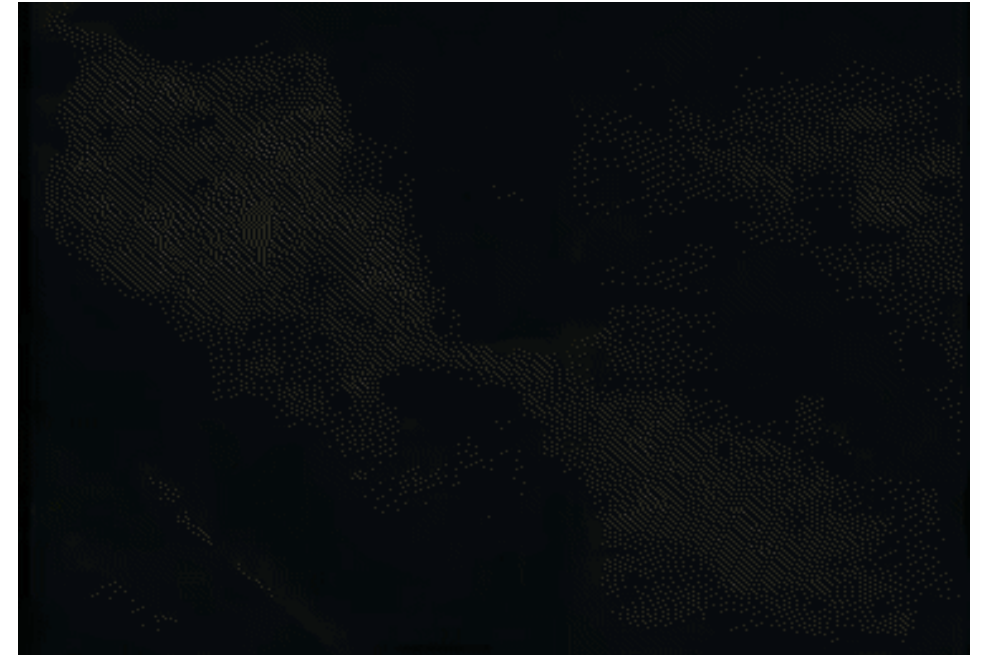
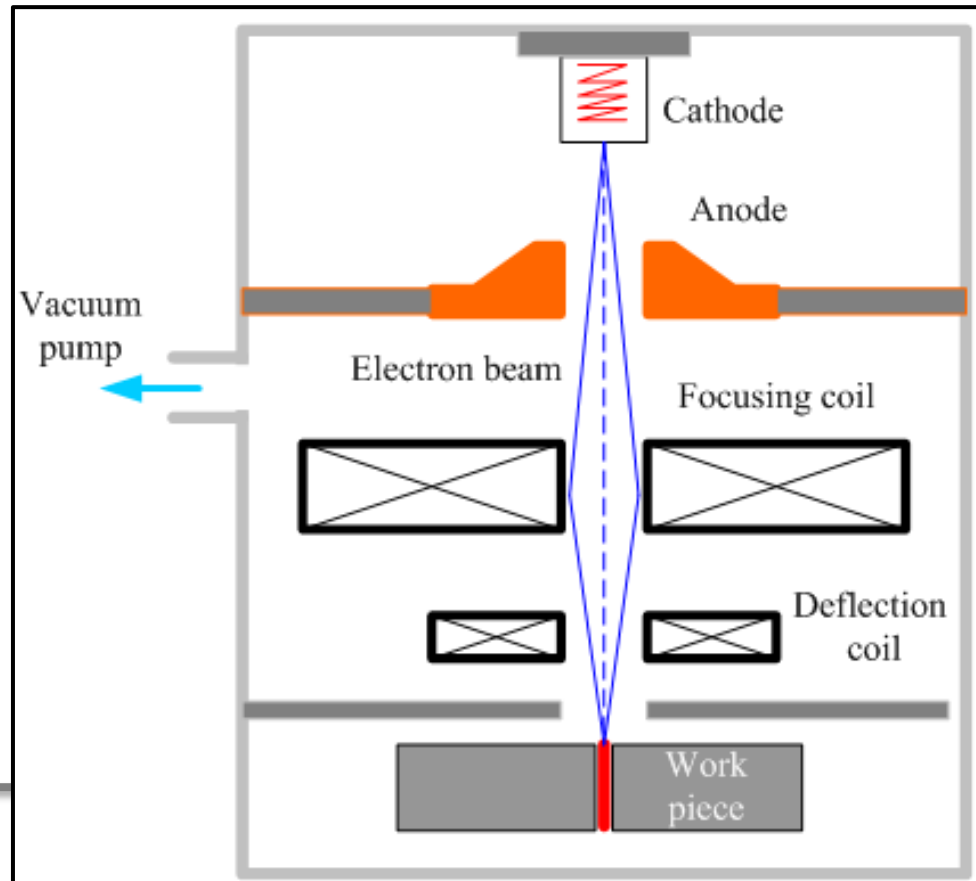
- Uses a laser beam to melt the metals; can be used for deep, narrow welds.
- Shielding gas: He-10%Ar.



Welding Classification: Energy source

➤ Electron Beam Welding (EBW)

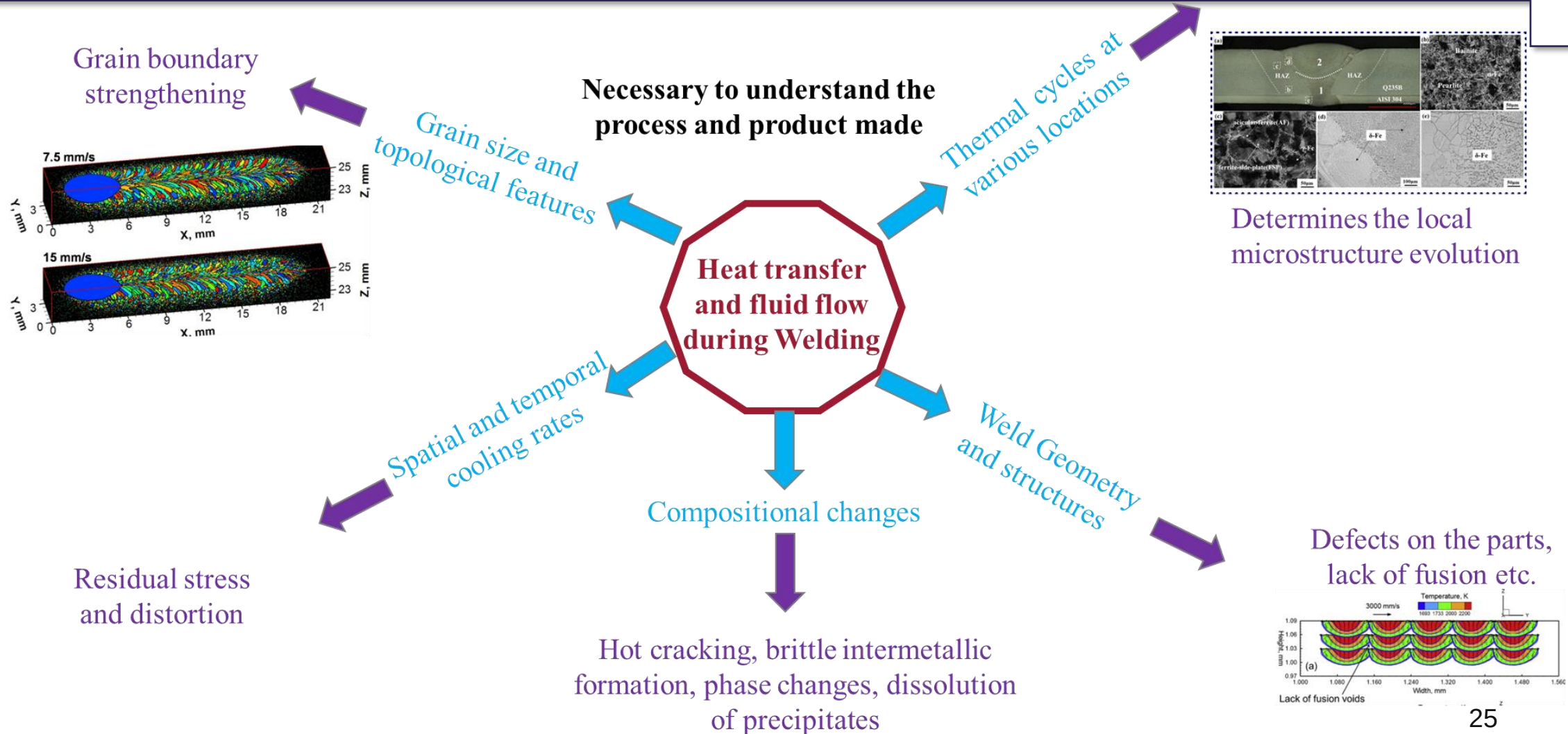
- Uses an electron beam to melt the metals in vacuum chamber; can be used for deep, narrow welds



Why is heat transfer and fluid flow important?



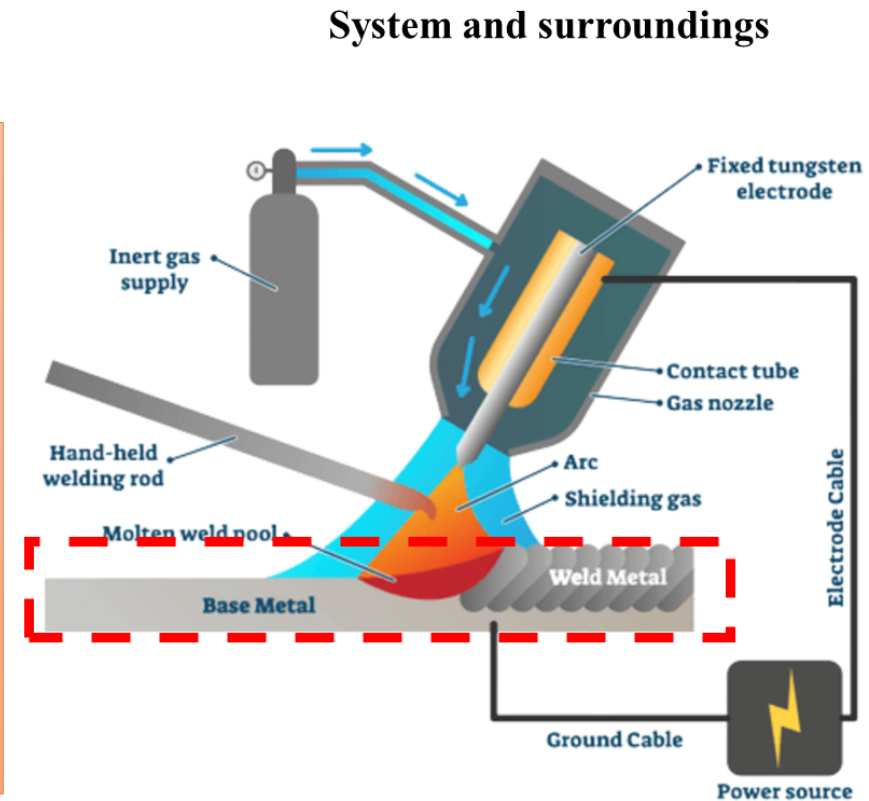
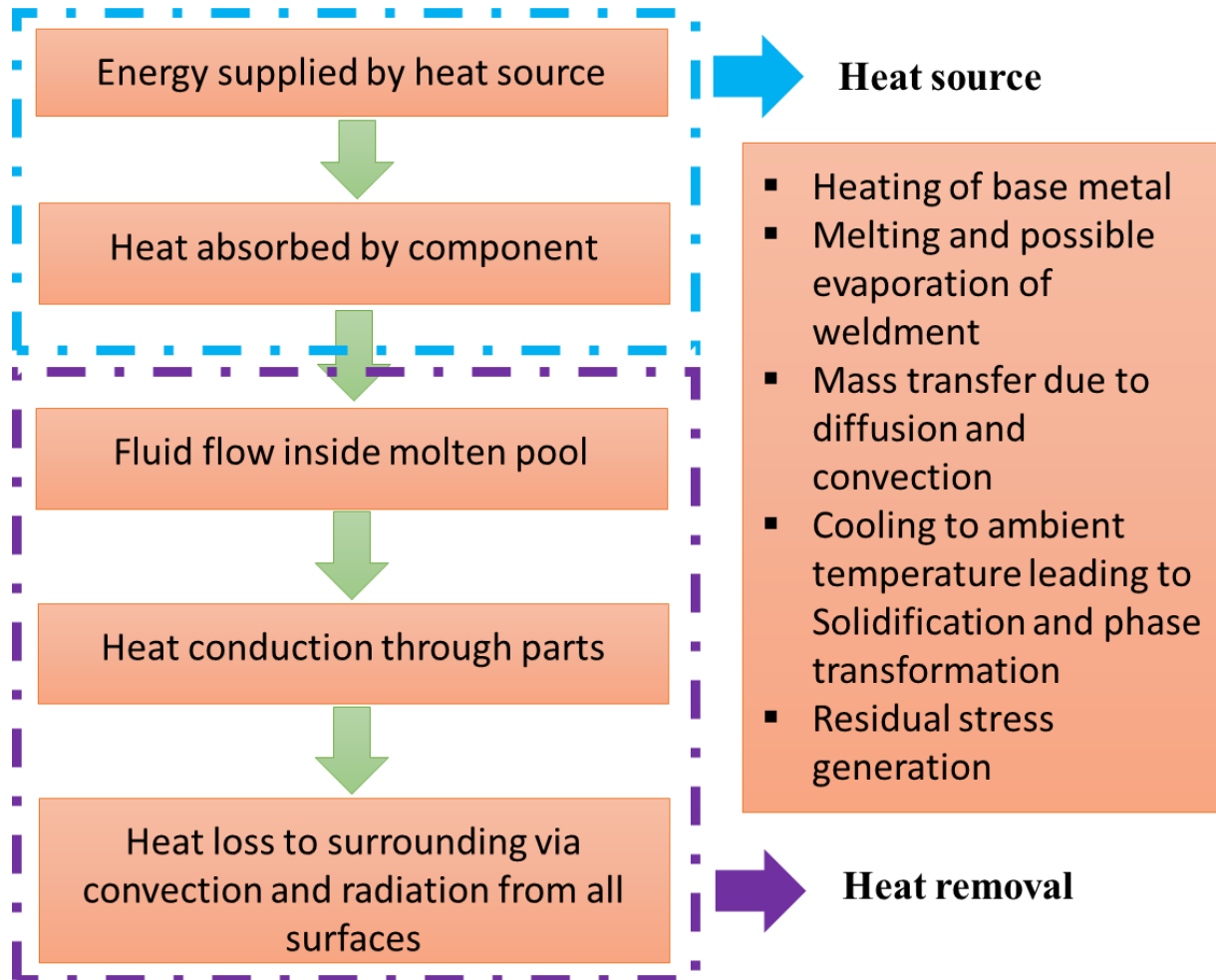
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Physical phenomena during fusion welding process



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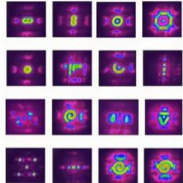


Characteristics of Heat source

Characteristics of Heat source:

- ☐ Nature of distribution
- ☐ Power distribution
- ☐ Absorption efficiency
- ☐ Temporal changes
- ☐ Traverse Rate
- ☐ Path of the heat source

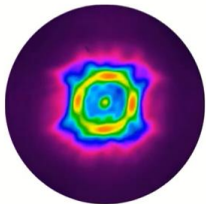
01.
Beam
Shaping.



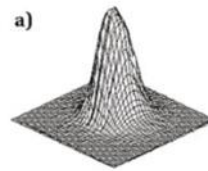
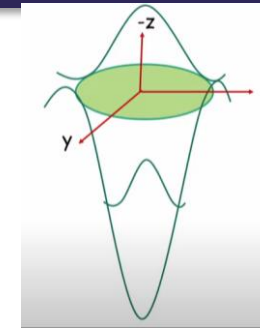
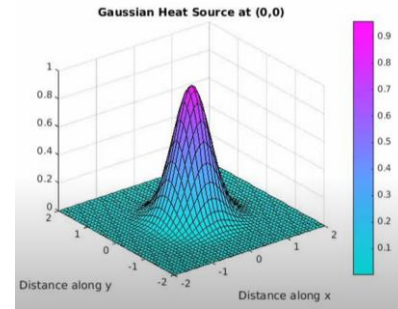
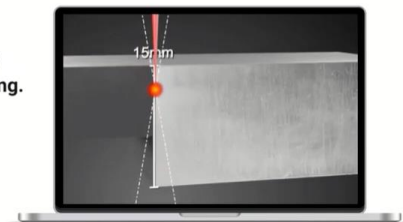
02.
Shape
Frequency.



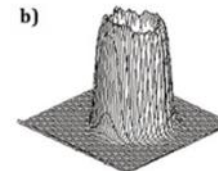
03.
Shape
Sequence.



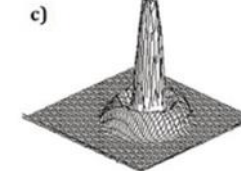
04.
Focus
Steering.



Gaussian
Beam



Doughnut
beam



ARM beam

Raster or Oscillations



Linear Path

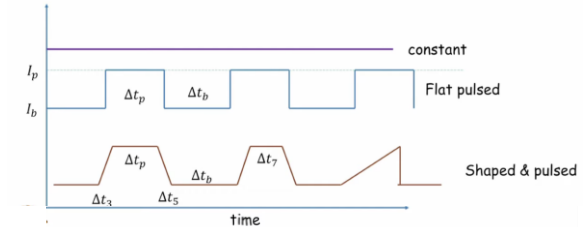


Raster Path



Oscillatory Path

Pulsing



Heat Transfer during welding



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Heat applied must be transferred!

Heat transfer

Conduction

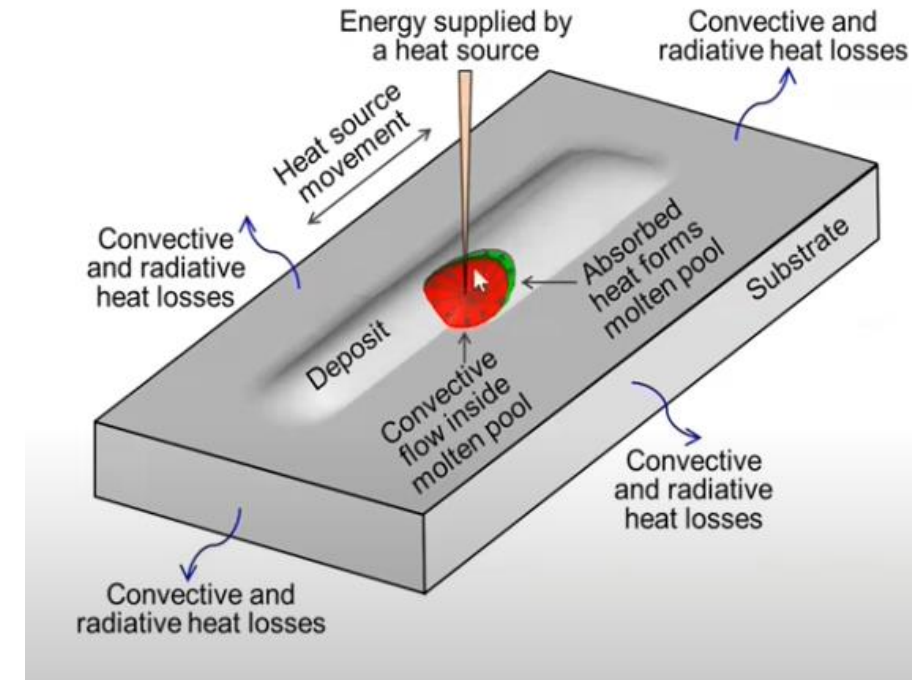
Convection

Radiation

Transfer of heat through a solid or stationary fluid (liquid or gas) due to molecular vibration and electron movement, without any bulk motion of the material

Convection is the transfer of heat from one place to another due to the combined effects of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow).

Radiation is the transfer of heat in the form of electromagnetic waves without requiring a medium.



Heat Transfer during welding



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Heat applied must be transferred!

Heat transfer due to conduction

$$q = -k \frac{dT}{dx}$$

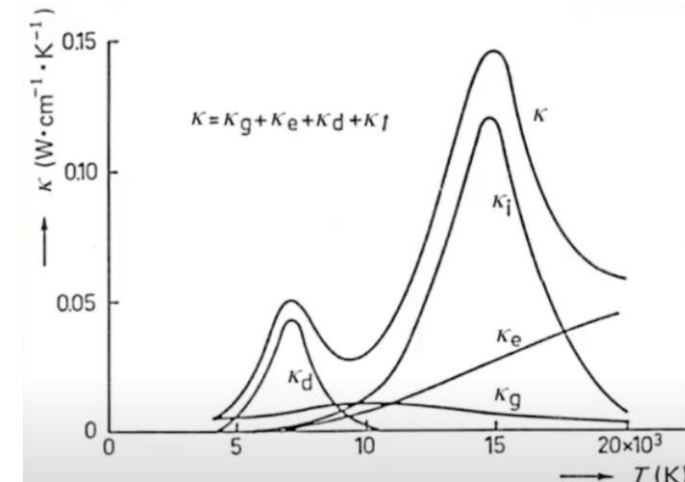
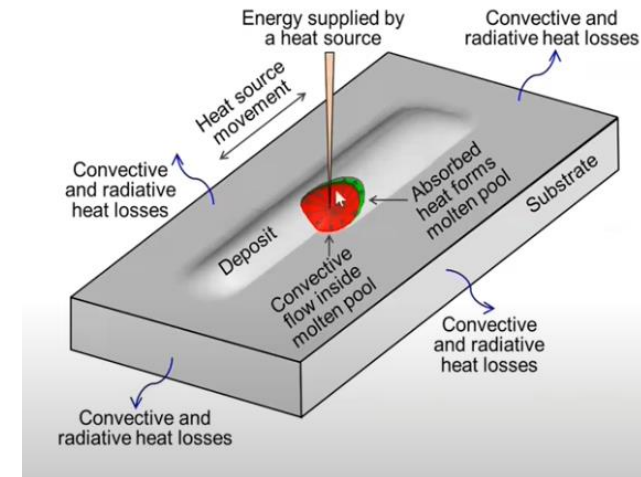
Fourier's law states that the amount of heat transfer from one end to another end is proportional to the temperature gradient and proportionality constant is heat transfer coefficient.

Heat transfer is quantified by heat transfer coefficient K .

Let's take an example of Arc welding, heat conduction takes place,

- By collision of heavy particles (atoms, gas and molecules), K_g classical heat transfer co-efficient
- By collisions of electrons and heavy particles K_e
- By diffusion of ionised pair (electrons and positive ions) K_i
- By diffusion of dissociated pair K_d

$$K = K_g + K_e + K_i + K_d$$



Heat Transfer during welding



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Heat transferred by convection

Convection is the transfer of heat from one place to another due to the combined effects of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow).

$$q = h A (T_s - T_0)$$

where h is the convective heat transfer coefficient, A is the surface area, T_s is the surface temperature, and T_0 is the fluid temperature.

- **Natural (free) Convection:** Occurs due to density variations within the fluid caused by temperature differences.
- **Forced Convection:** Occurs when an external force, such as a fan, pump, or blower, causes fluid movement

Heat transferred by radiation

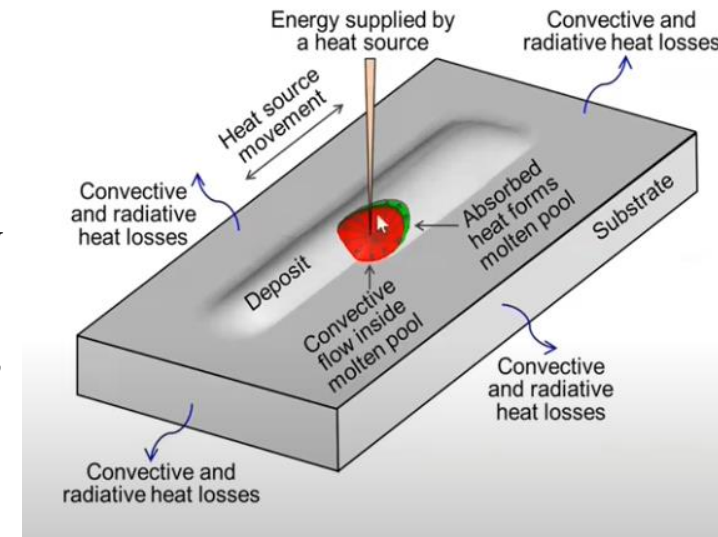
Radiation is the transfer of heat in the form of electromagnetic waves without requiring a medium.

$$q = \varepsilon \sigma A T^4$$

where,

q = radiative heat transfer rate, ε = emissivity (ranges from 0 to 1, with 1 being a perfect black body)

σ = Stefan-Boltzmann constant, A = surface area (m^2), T = absolute temperature (K)



Heat Transfer during welding

Heat Flow through weldments

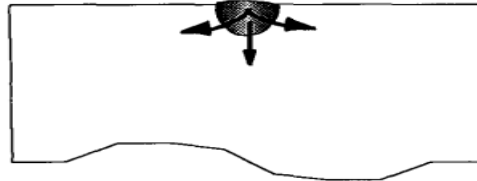
Heat flow in the material is determined by:

- workpiece thickness
- Heat flow paths, edge, end effects
- Convection in the weld pool
- Heat source distribution
- Material properties: thermal conductivity and specific heat, latent heat absorption and release

Effect of relative plate thickness

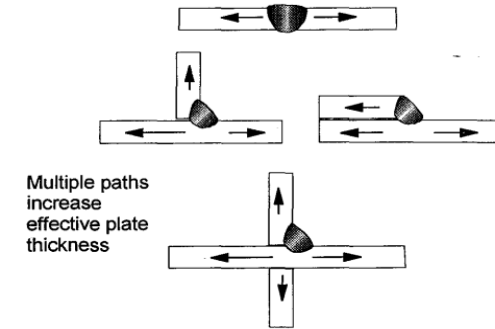


(a) Thin Plate: 2-D Heat Flow

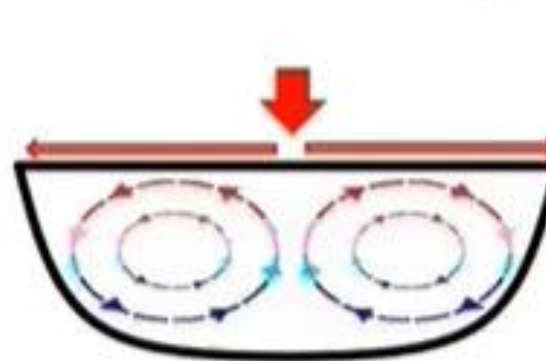


(b) Thick Plate: 3D Heat Flow

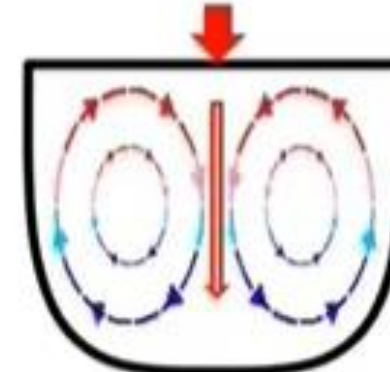
Effect of heat flow paths



Convection in the molten pool



Hot liquid flows outward

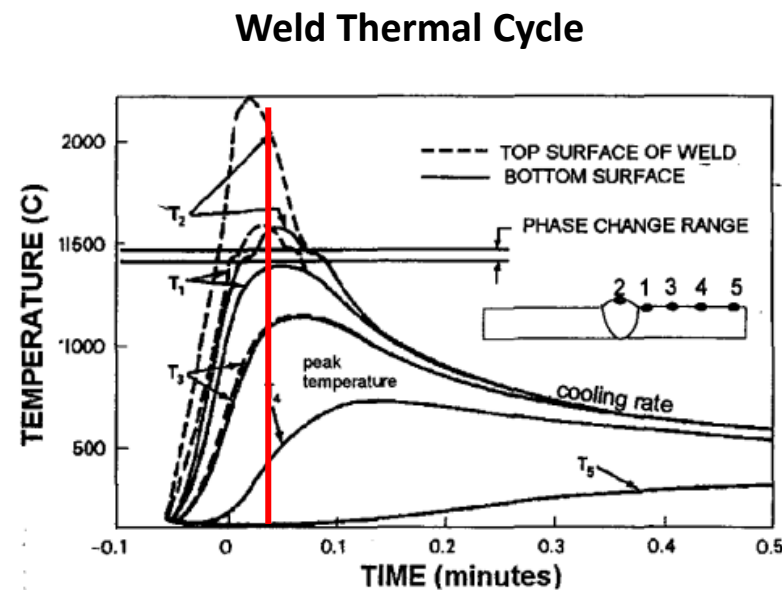


Hot liquid flows downward

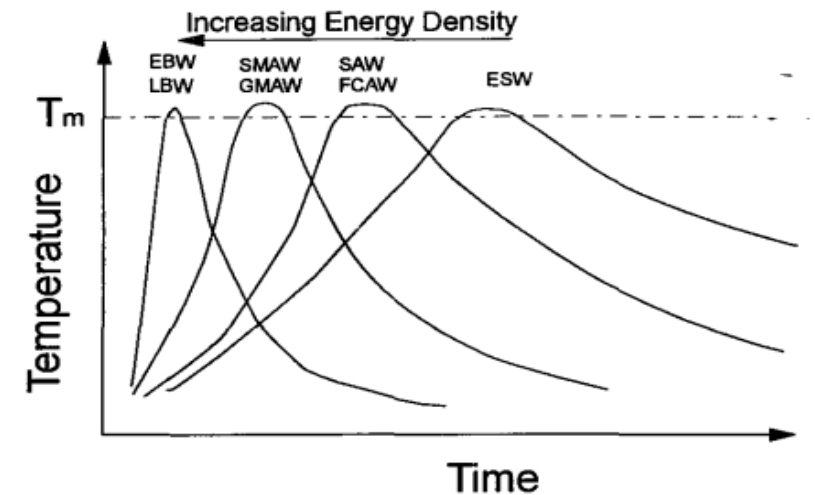
Heat Transfer during welding

Significance of Thermal Effects

- The thermal conditions in and near welds govern the resulting metallurgical structure, mechanical properties, residual stress and distortion
- Of particular significance are:
 - Weld bead area
 - Weld solidification rate
 - Peak temperatures in the HAZ
 - Width of HAZ
 - Cooling rates in the weld and HAZ



Thermal cycles of different welding processes



Fluid flow during welding



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What causes convection inside the melt pool?

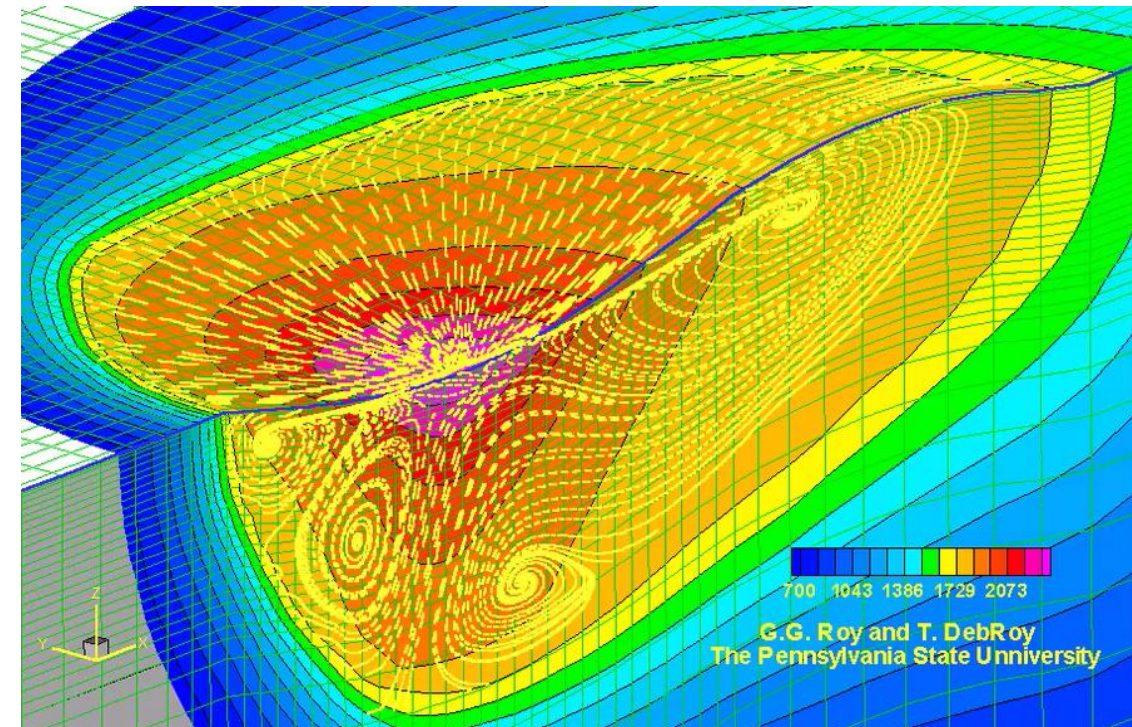
There are five factors that governs the flow of liquid metal within the weld pool

1. Buoyancy Force
2. Electromagnetic force (Lorentz Force)
3. Shear stress induced by surface tension gradient (Marangoni convection)
4. Shear stress acting on the pool by the gas flow
5. Forced convection (due to arc pressure or beam oscillation)

Strength of flow:

Surface tension force > **Electromagnetic force** >> **Buoyancy force** >> **Arc pressure**

← **Forced convection** →

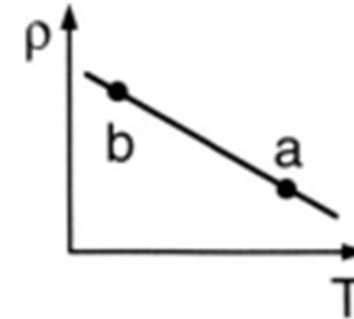


Fluid flow during welding

Driving forces for weld pool convection: Buoyancy Force

1. (a) Thermal Buoyancy Force:

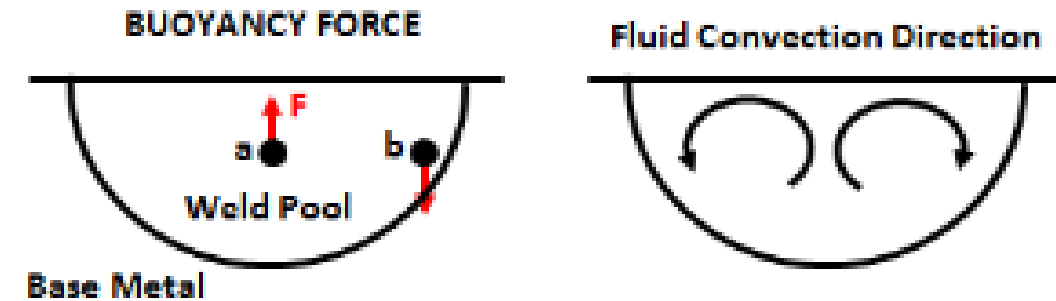
Density changes with change in temperature which leads to rise of hot liquids and cold liquids sinks. So, gravitational force leads to convective flow pattern.



Cooler liquid metal at point **b** is heavier than point **a** causing gravity sinks along the pool boundary and rises along the pool axis

1. (b) Solutal Buoyancy Force:

Density changes are because of solute or concentration differences. Concentration is a function of location within the melt pool such as during dissimilar welding or addition of filler wire.



Wide and shallow weld

Fluid flow during welding

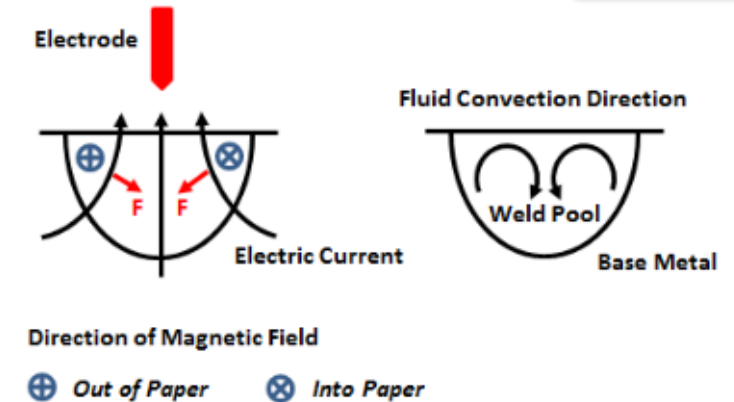


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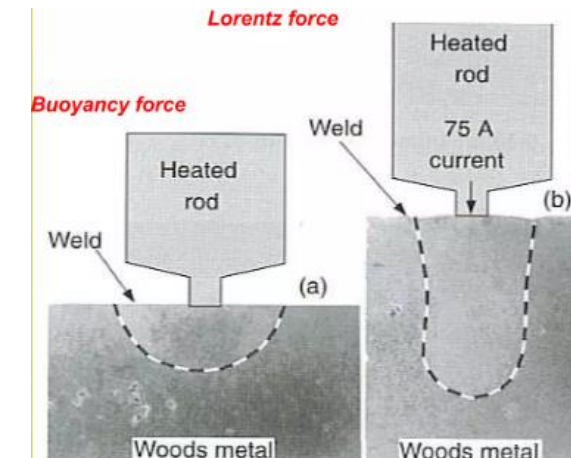
Driving forces for weld pool convection: Electromagnetic force

2. Electromagnetic Force:

- During arc or electron beam welding current is going through the sample and part of the body is actually liquid which can move and induces a magnetic field.
- Coupling magnetic field and current leads to the generation of Lorentz force which causes convective flow.
- The electromagnetic force $\vec{F}_{em}$ or Lorentz force, is governed by
$$\vec{F}_{em} = \vec{J} \times \vec{B}$$
 where $\vec{J}$ and $\vec{B}$ are the current density and magnetic flux vector
- The Lorentz forces causes deeper weld as compared to the Buoyancy force as it pushes the liquid metal downward and carries heat from the heat source to the bottom.



Narrow and deeper weld

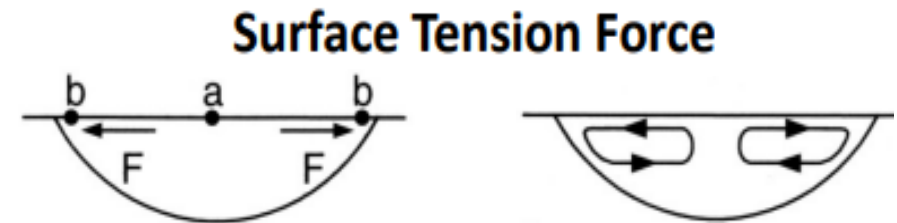
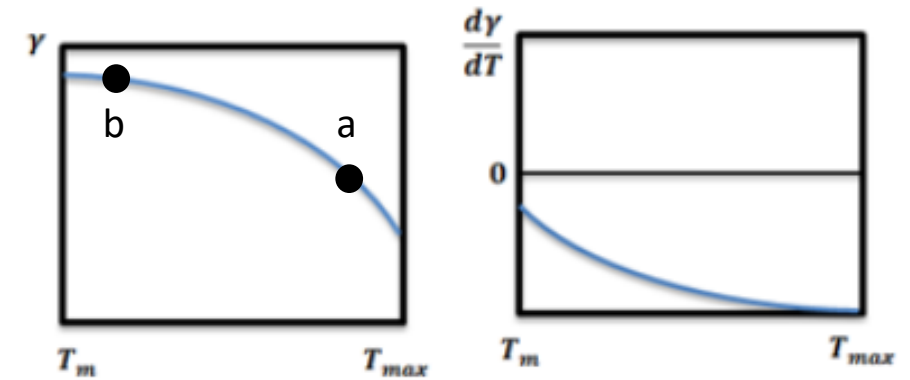


Fluid flow during welding

Driving forces for weld pool convection: Surface Tension Force

3. (a) Surface Tension Force : Thermal Marangoni

- Occurs due to gradients in surface tension due to temperature differences (thermal Marangoni effect).
- Warmer liquid metal having a lower surface tension at point **b** pulls out the liquid metal in the middle point **a** along the pool surface.
- The liquid in the melt pool is going to convect to minimise the surface energy.
- The way it can minimise it by having more area having low surface tension or less area with high surface tension.



Wide and shallow weld

Fluid flow during welding

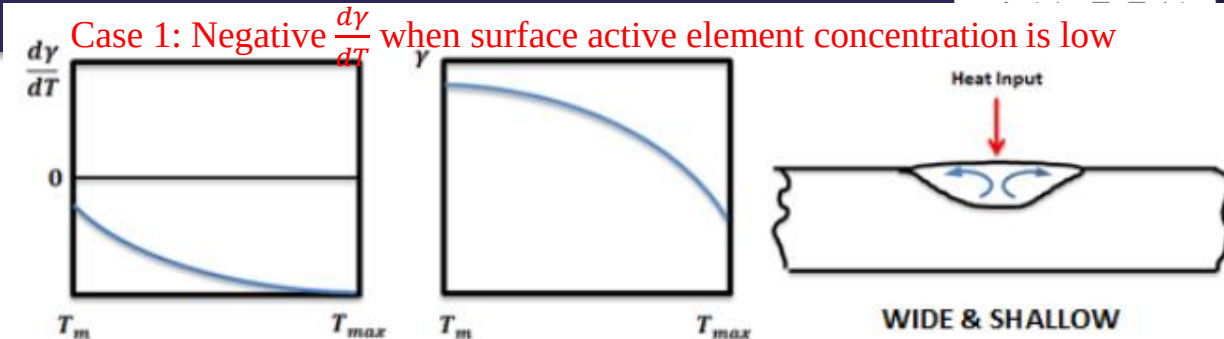


Driving forces for weld pool convection: Surface Tension Force

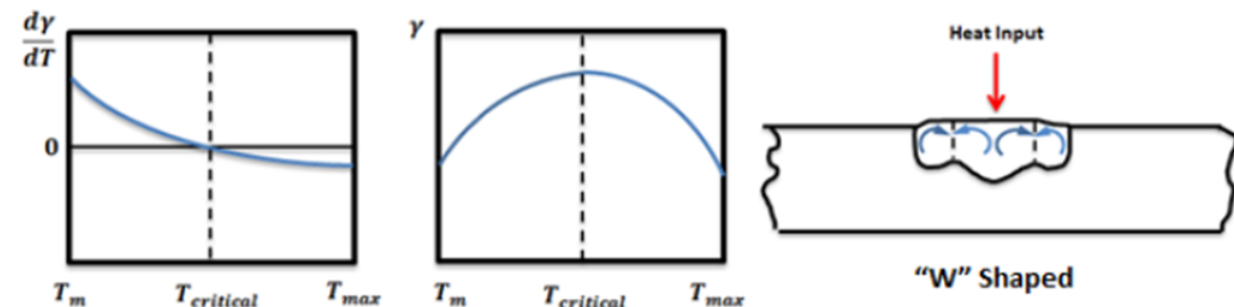
3. (b) Surface Tension Force: Solutal Maragoni

- Occurs due to gradients in surface tension due to compositional differences (solutal Marangoni effect).
- The surfactants such oxygen, sulphur tend to go to surface and segregate and alter the temperature coefficient of surface tension (dy/dT). Instead of decreasing with temperature, surface tension increases with temperature.
- This leads to flow radially outward leading to shallow and wide molten pool.

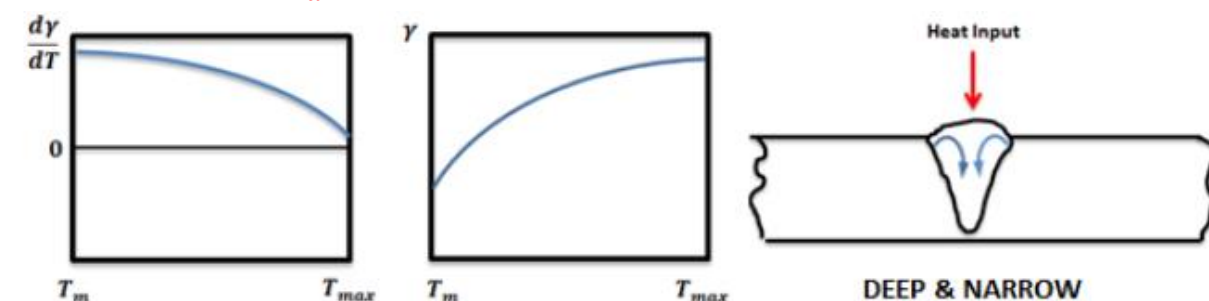
Lee Aucot, Mechanism of solidification cracking during welding of high strength steels for subsea linepipe, 2015



Case 2: $\frac{dy}{dT}$ can be both positive and negative across the pool when surface active element concentration is increased



Case 3: Positive $\frac{dy}{dT}$ when surface active element concentration is high

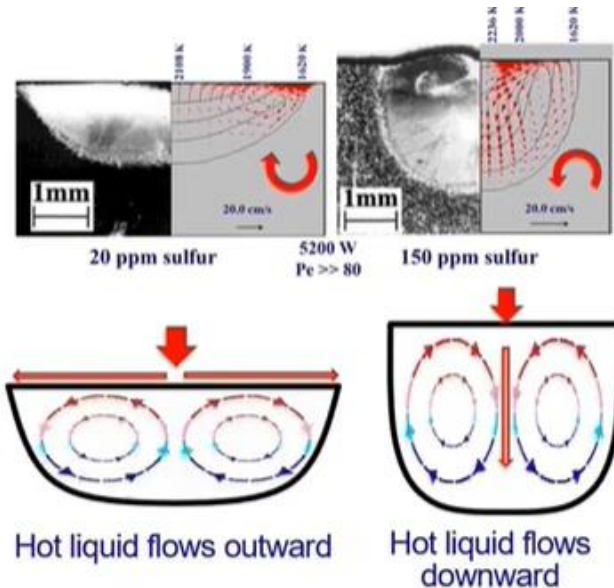


Fluid flow during welding

Driving forces for weld pool convection: Surface Tension Force

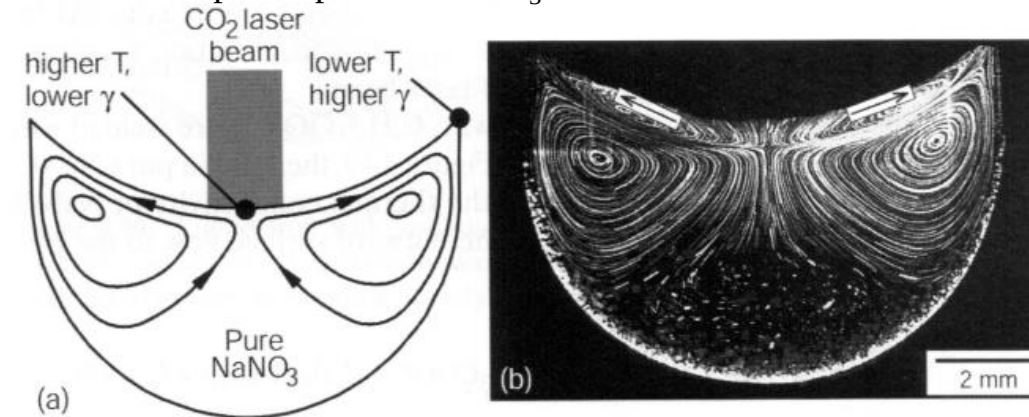
Reverse Marangoni Convection

- The direction of the flow changes from outward to inward on the surface due to the addition of surface-active agent.
- A reverse Marangoni convection makes the weld pool deeper

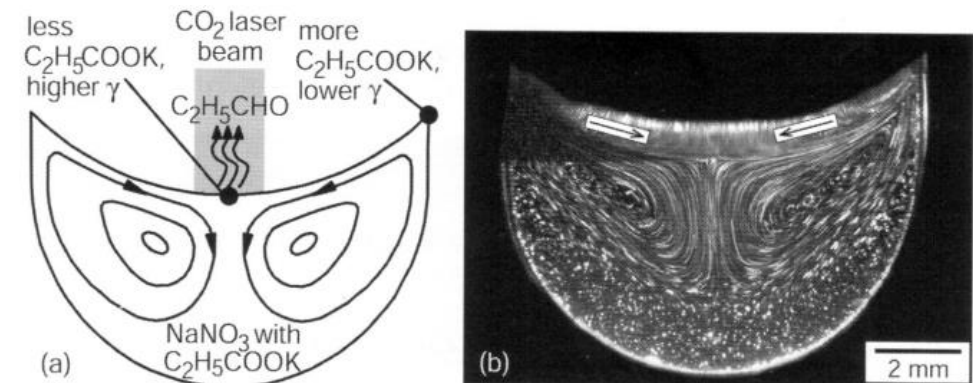


Effect of Sulphur on flow direction

Flow in transparent pool of NaNO_3



Addition of 2% $\text{C}_2\text{H}_5\text{CHO}$ reduces surface tension of NaNO_3 pool



Fluid flow during welding

Driving forces for weld pool convection: Gas flow

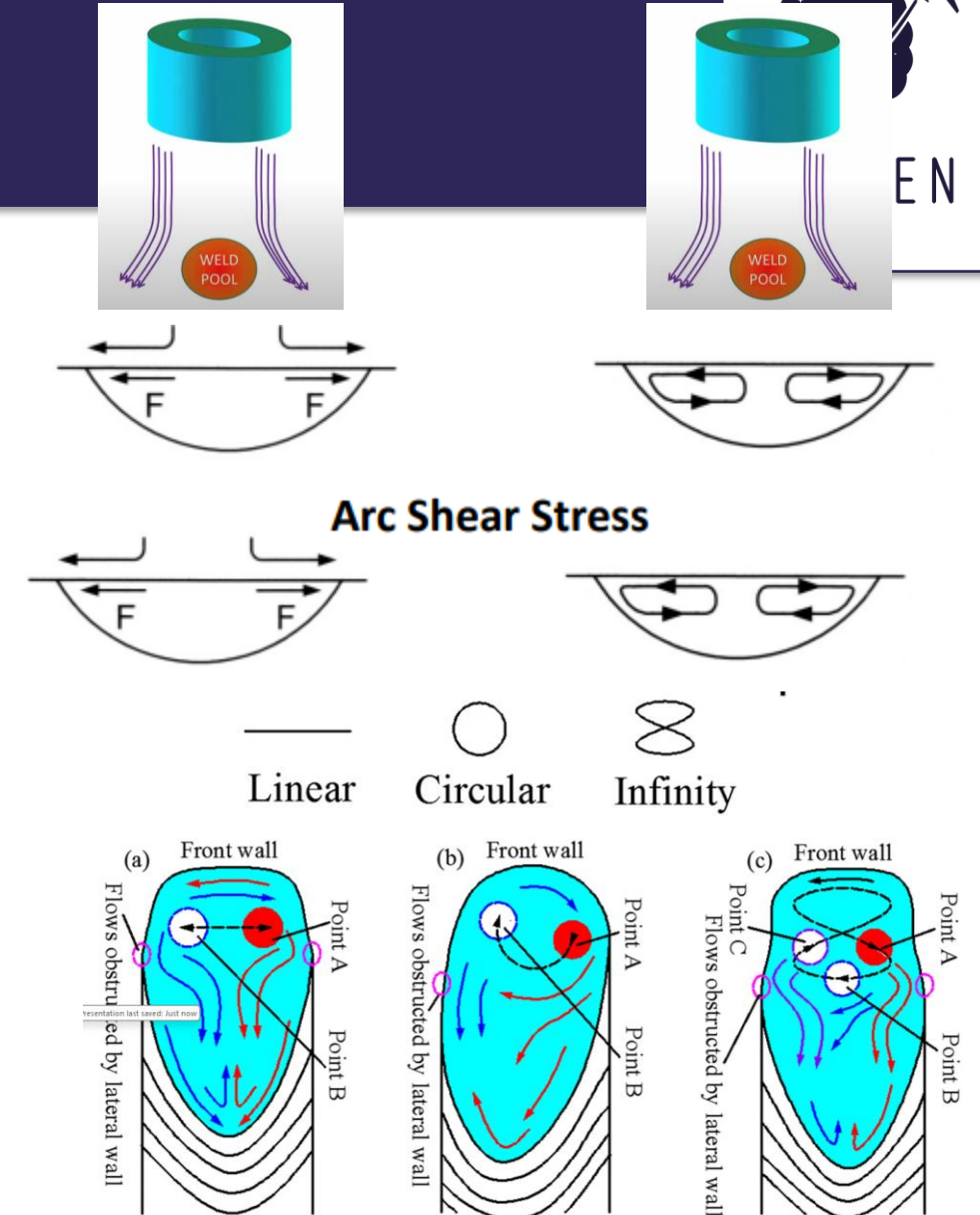
4. Shear stress acting on the pool by the gas flow:

- On top of the molten pool, we have gas shroud and gas is going away
- While going away it can exert certain amount of stress on the surface of the molten pool to move in the outwards direction.

Driving forces for weld pool convection: Forced convection

5. Forced convection (due to arc pressure or beam oscillation):

- Arc Pressure: High speed outward movement of plasma arc leads to outward shear stress causing metal flowing outwards.
- Beam Oscillation: Churning action caused by the oscillating beam induces forced convection and depends on the oscillation pattern.
- Magnetic stirring: Magnetic field is applied to the molten metal pool during a welding process, causing the liquid metal to swirl and mix





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Governing Equations for heat transfer, fluid flow and mass transport model

Heat Transfer Model:

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P u \cdot \nabla T = \nabla \cdot (\lambda \nabla T) + Q_{laser} + Q_{vap} \quad \text{----(1)}$$

$$Q_{mass} = \frac{\alpha}{\sqrt{2\pi RT}} \cdot (P_{sat} - P_{vap}) \quad \text{----(2)}$$

Energy Conservation:

Fluid Flow Model:

$$\nabla \cdot u = 0 \quad \text{----(4)}$$

Mass Conservation Equation:

$$\rho \frac{\partial u}{\partial t} = -\rho(u \cdot \nabla)u - \nabla P + \nabla \cdot \eta(\nabla u) + F \quad \text{----(5)}$$

$$F = J \left(-\frac{(1 - f_l)^2}{f_l^3 + B} \right) u + \rho g \beta (T - T_{melting}) + \rho g \beta_c (C - C_{ref}) \quad \text{----(6)}$$

$$P_{sat} = P_v \cdot \exp \left(\frac{\Delta H_v}{(\gamma - 1) \cdot c_v T_v} \left(1 - \frac{T_v}{T} \right) \right) \quad \text{----(3)}$$

$$P_{recoil} = A_r \cdot \exp \left(B \cdot \left(1 - \frac{T_v}{T} \right) \right) \quad \text{----(7)}$$

Mass Transport Model:

$$\frac{\partial(\rho C_i)}{\partial t} + \nabla \cdot (uC) = \nabla \cdot \left(D_i \nabla C_i + D_{Ti} \frac{\nabla T}{T} \right) \quad \text{----(8)}$$

Tracking of Keyhole using VOF method:

$$\frac{\partial f}{\partial t} + \nabla(\vec{V}f) = 0. \quad \text{----(9)}$$

Anand Mohan, et al, Modelling of thermal quantities in laser welded joints for process assessment and parameters selection at the early design phase, Int J Adv Manuf Technol (2022)

Anand Mohan, et. al, Impact of energy distribution on the microstructure and mechanical performance in Adjustable Ring Mode (ARM) remote laser welding of high strength aluminium alloys, Journal of Materials Research and Technology (2022)

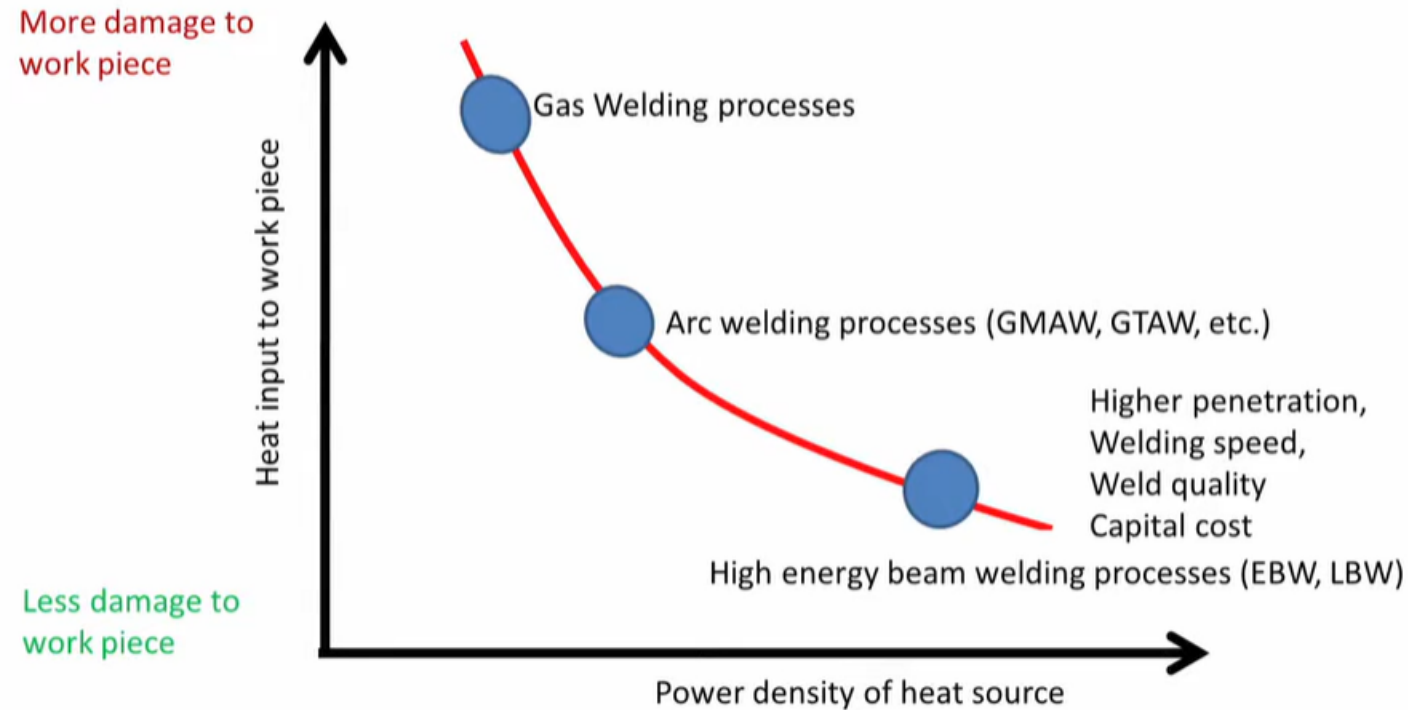
Anand Mohan, et al. Numerical study of beam oscillation and its effect on the solidification parameters and grain morphology in remote laser welding of aluminium, Science and Technology of welding and joining (2023)

Why Laser welding?



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Heat input vs power density



Fundamentals of Laser



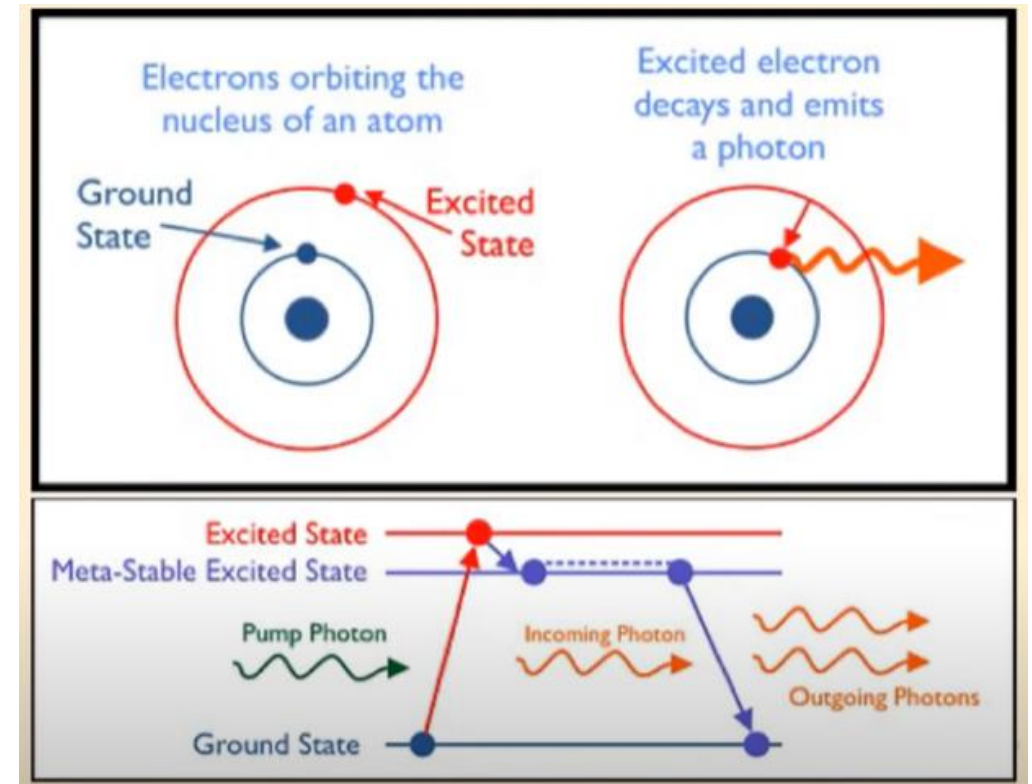
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Is LASER a device or a process?

Light
Amplification by
Stimulated
Emission of
Radiation

A **laser** (Light Amplification by Stimulated Emission of Radiation) is fundamentally a **device** that emits a highly focused, coherent, and monochromatic beam of light.

The term **laser** can also refer to the **process** of generating light through stimulated emission.



Fundamentals of Laser

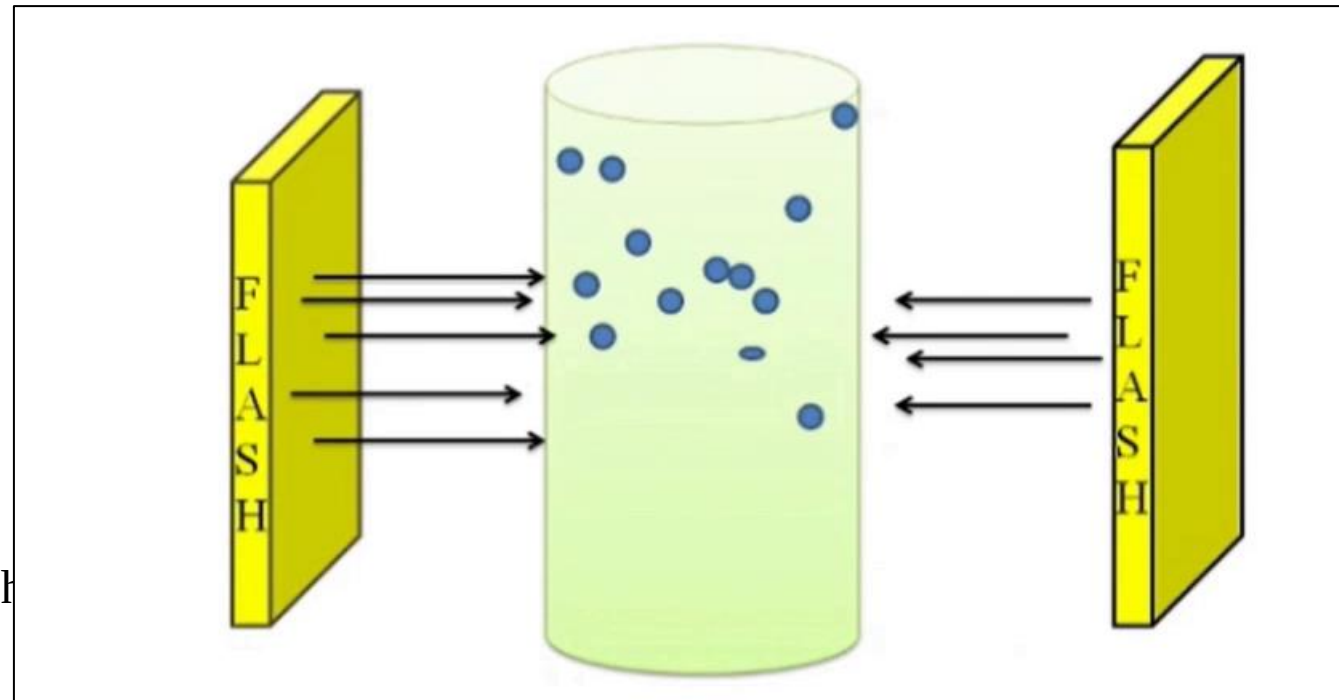


Light
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Is LASER a device or a process?

A **laser** (Light Amplification by Stimulated Emission of Radiation) is fundamentally a **device** that emits a highly focused, coherent, and monochromatic beam of light.

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Types of Lasers Used in Laser Welding



◆ Gas Lasers

•CO₂ Laser

- Wavelength: 10.6 μm (infrared)
- High power, deep penetration
- Suitable for thick materials (steels, alloys)

◆ Solid-State Lasers

•Nd:YAG Laser (Neodymium-doped Yttrium Aluminium Garnet)

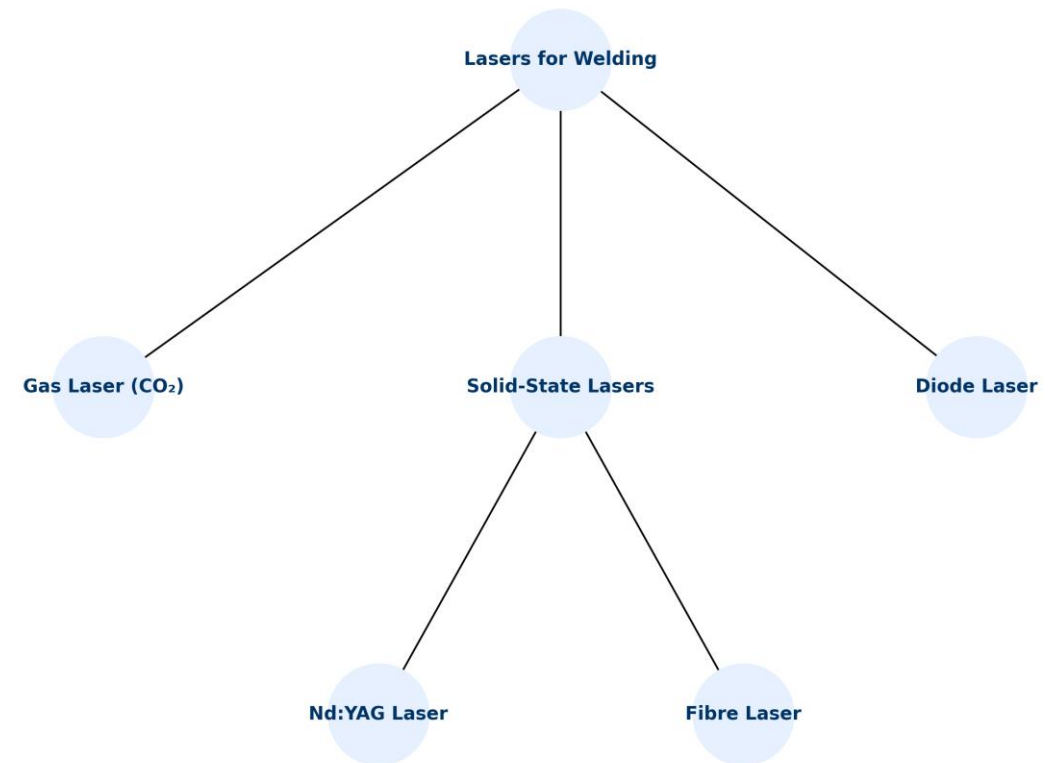
- Wavelength: 1.06 μm
- Can be delivered via fibre optics
- Good for precision welding, automotive & electronics

•Fibre Laser

- Wavelength: 1.06 μm (similar to Nd:YAG)
- High beam quality & efficiency
- Excellent for high-speed welding, thin to medium sections

◆ Diode Laser

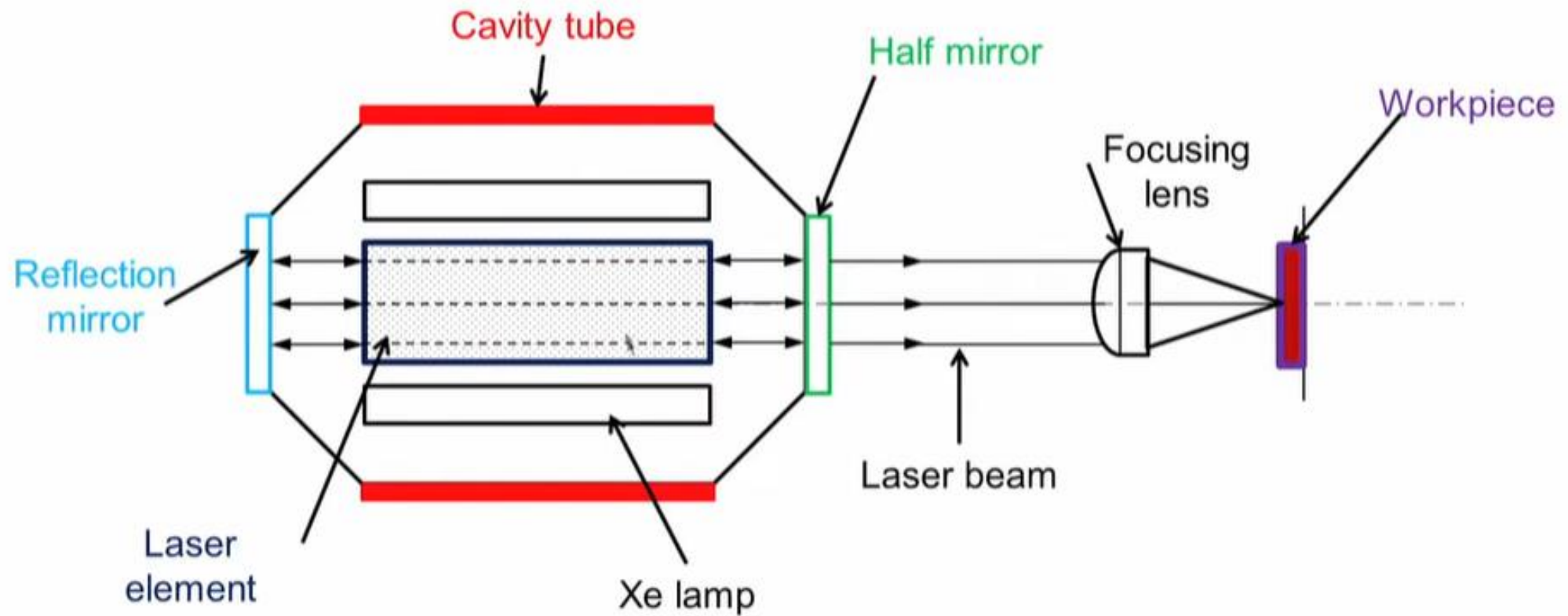
- Wavelength: $\sim 0.8\text{--}1.0\ \mu\text{m}$
- Compact, energy-efficient
- Common in low-to-medium power welding & cladding



Laser Welding Setup: Basic



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Laser Beam optics



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Application: focus, modify and shape the laser beam

Short focal length: Faster weld speed, Less heat input

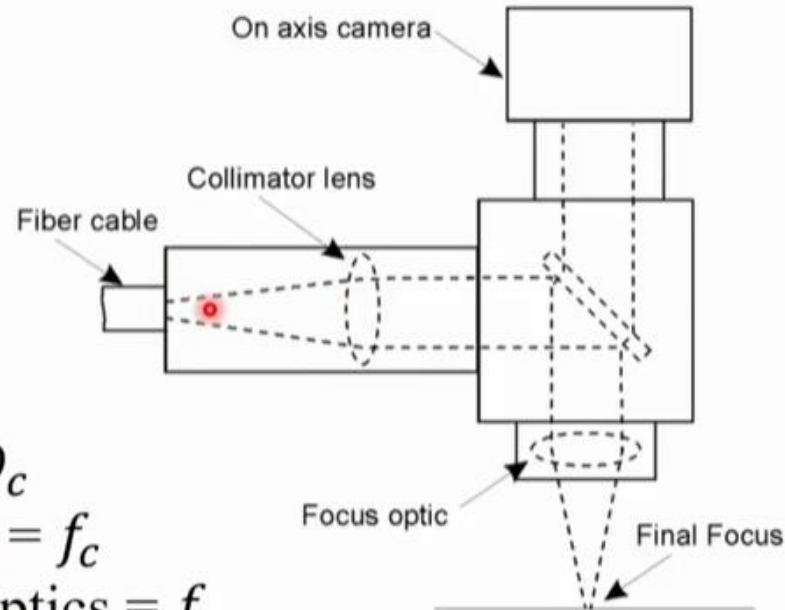
Long focal length: Longer depth of focus, Further from weld spatter & smoke

Core diameter of fiber = D_c

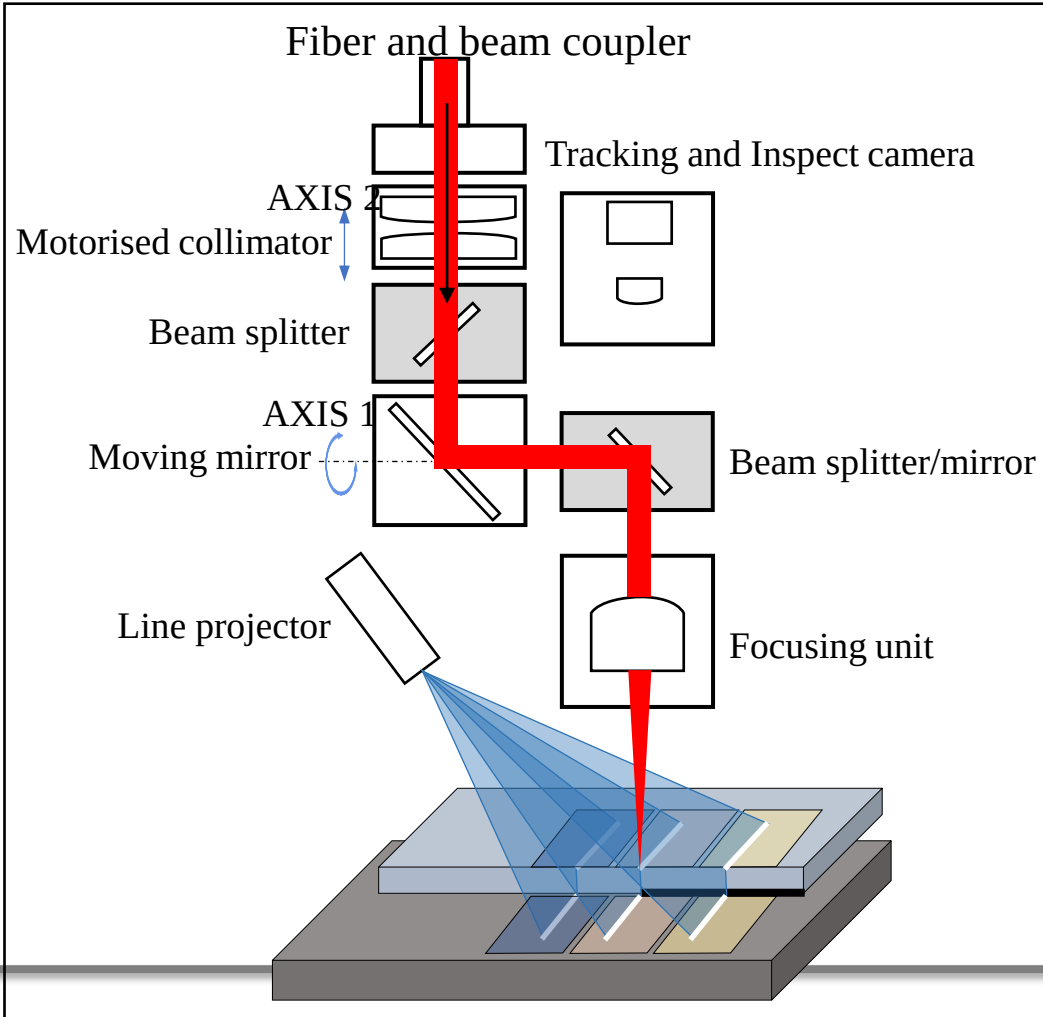
Focal length of collimator = f_c

Focal length of focusing optics = f_o

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



Laser Welding Setup: Advanced



Optical paths

- Main beam delivery
- Pre-process monitoring & post-process monitoring
- In-process monitoring

Wavelength spectrum: $\sim 1080\text{nm}$ (laser radiation)

Laser Welding Setup: Advanced

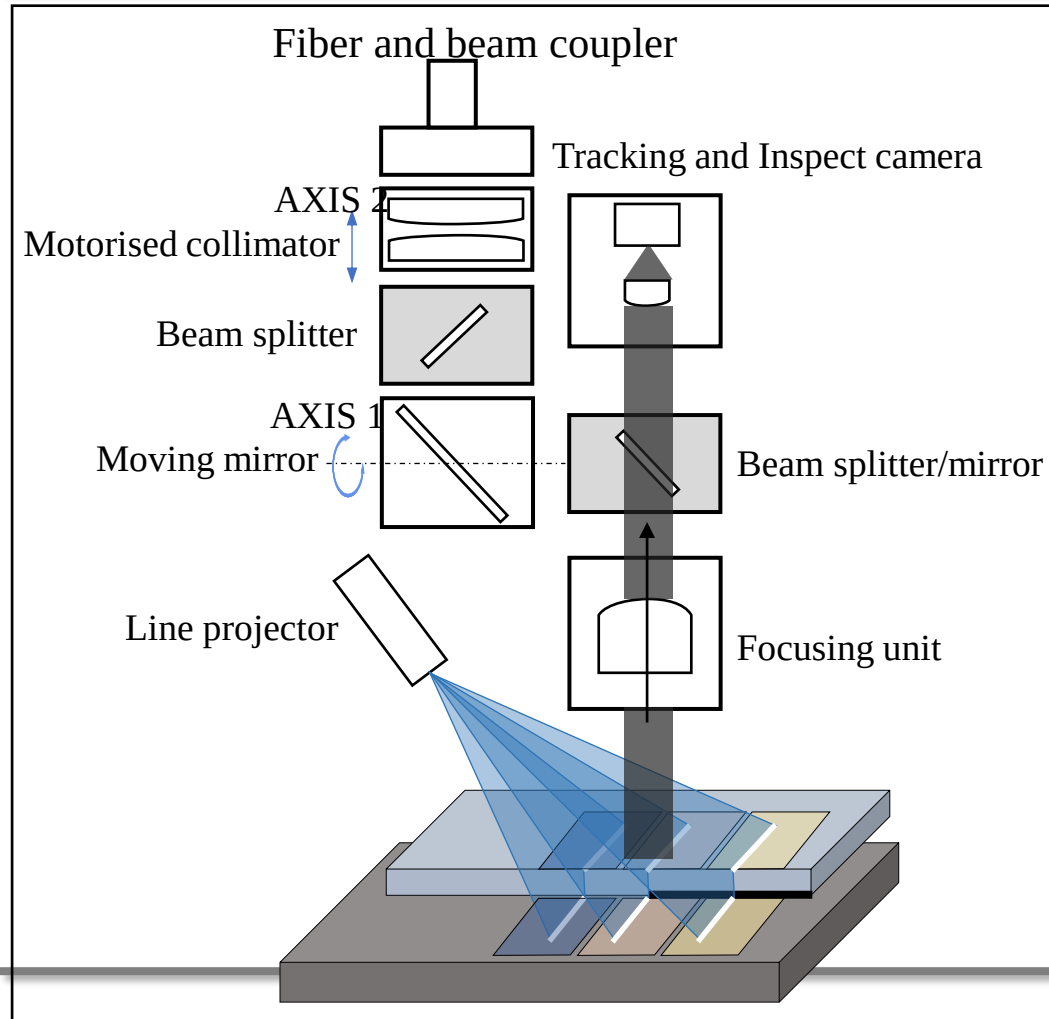


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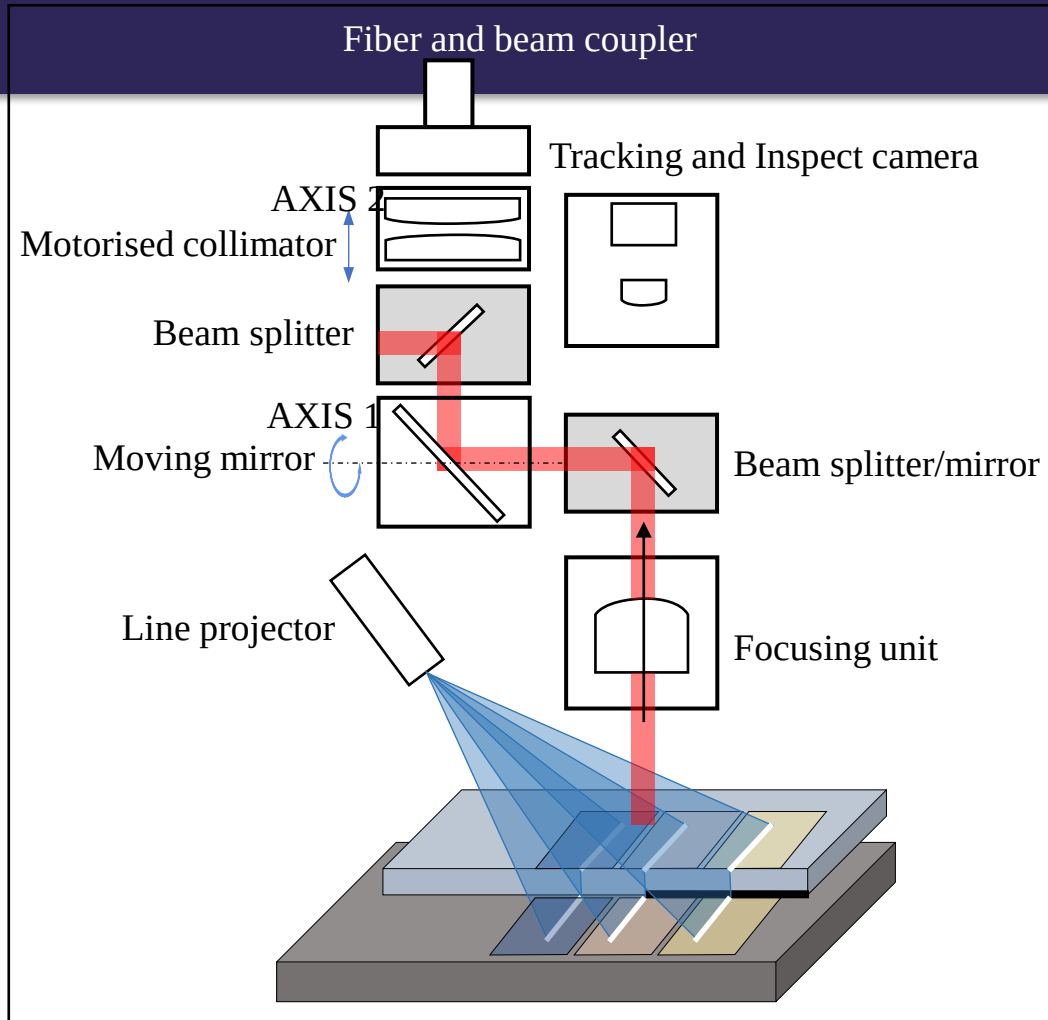
Optical paths

- Main beam delivery
- Pre-process monitoring & post-process monitoring
- In-process monitoring

Wavelength spectrum: 400 to 600nm (Visible)



Laser Welding Setup: Advanced

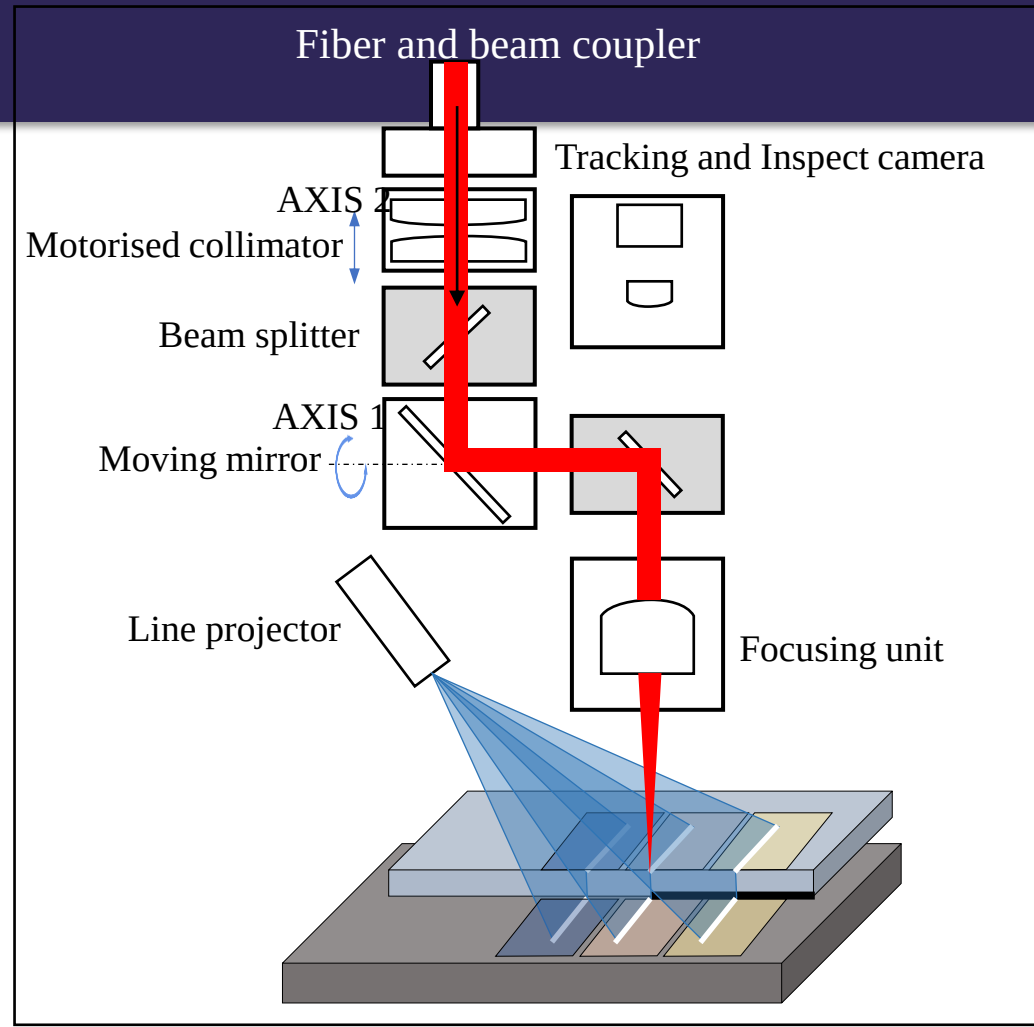


Optical paths

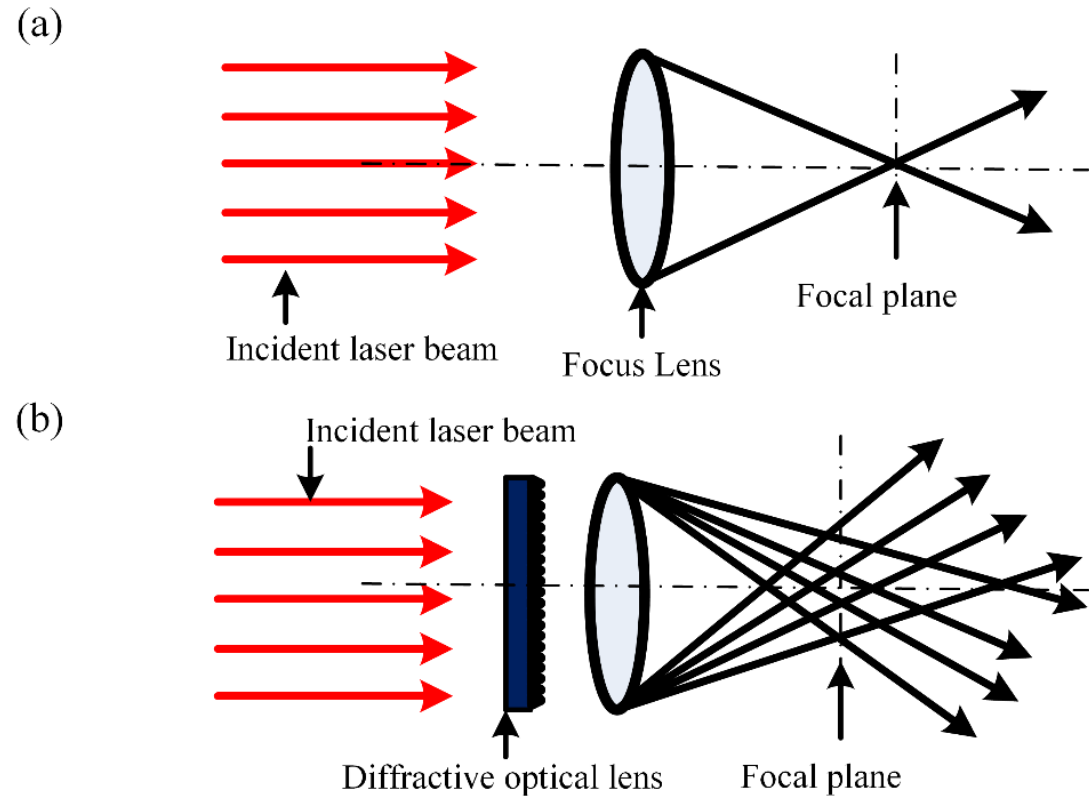
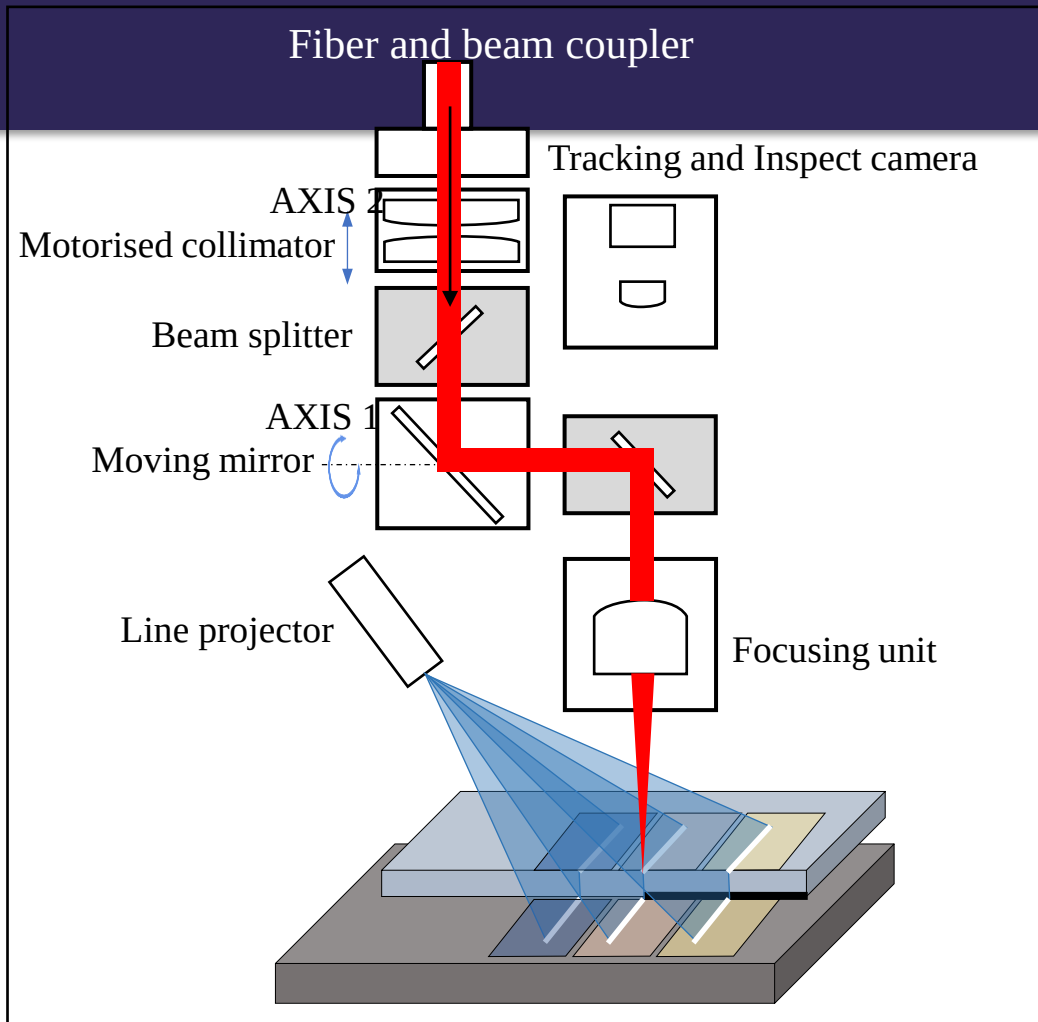
- Main beam delivery
- Pre-process monitoring & post-process monitoring
- In-process monitoring

Wavelength spectrum: ~200 (UV) to 800nm (NIR)

Laser Welding Setup: Beam Shaping



Laser Welding Setup: Beam Shaping

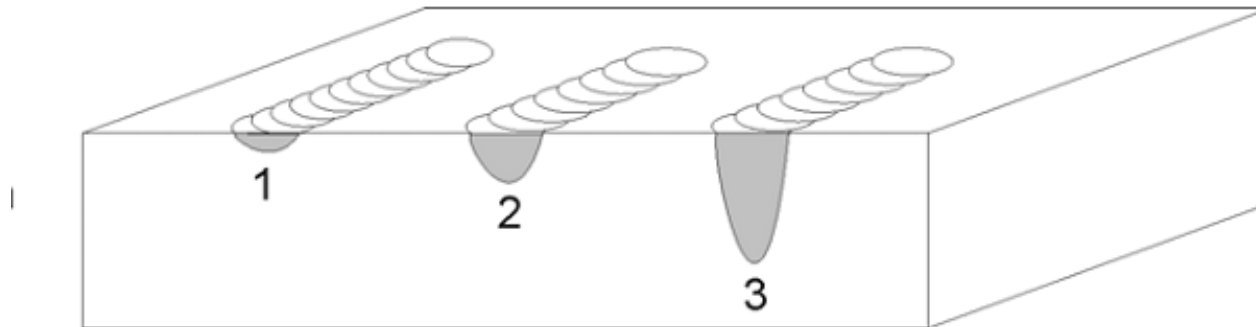


Modes of Welding: Conduction vs Keyhole welding



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- Laser welding is a non-contact process that requires access to the weld zone from one side of the parts being welded
- The weld is formed as the intense laser light rapidly heats the material-typically calculated in milli-seconds.
- There are typically three types of welds:
 1. –Conduction mode
 2. –Conduction/penetration mode
 3. –Penetration or keyhole mode.

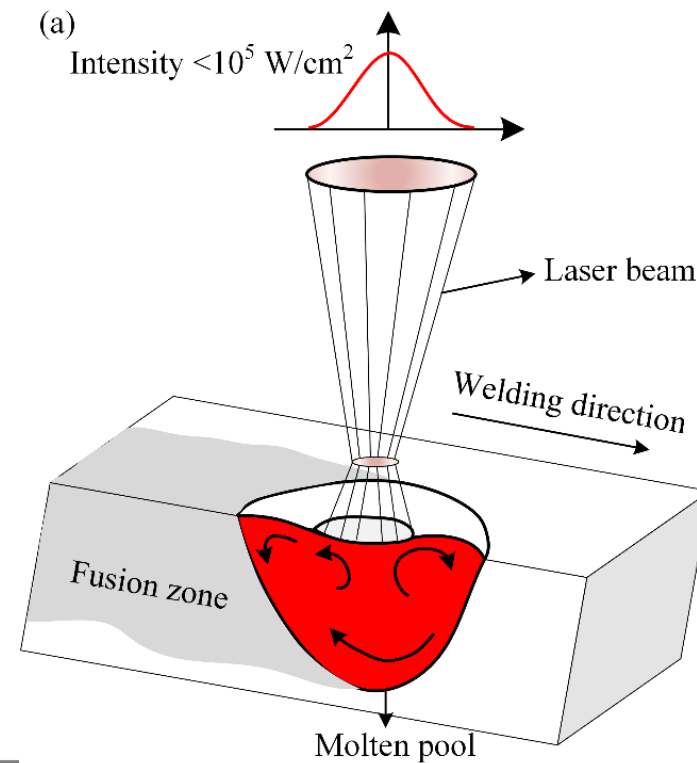
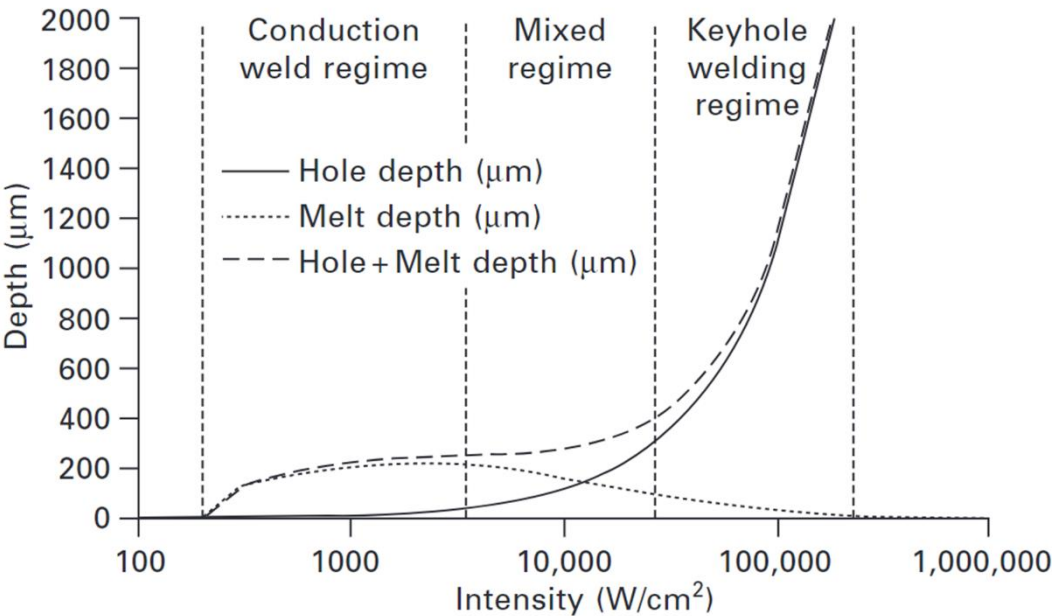


Modes of Welding: Conduction vs Keyhole welding

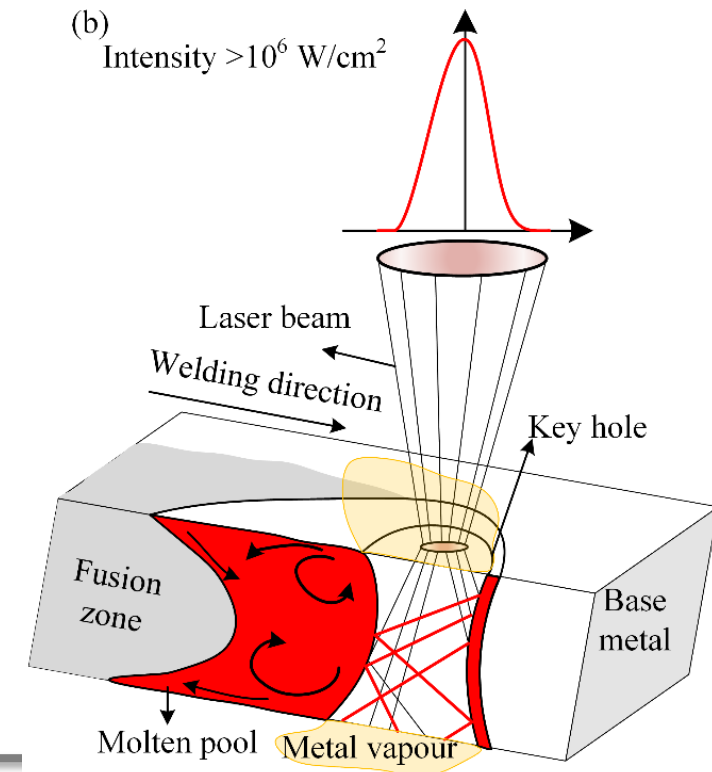


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Conduction mode of Welding



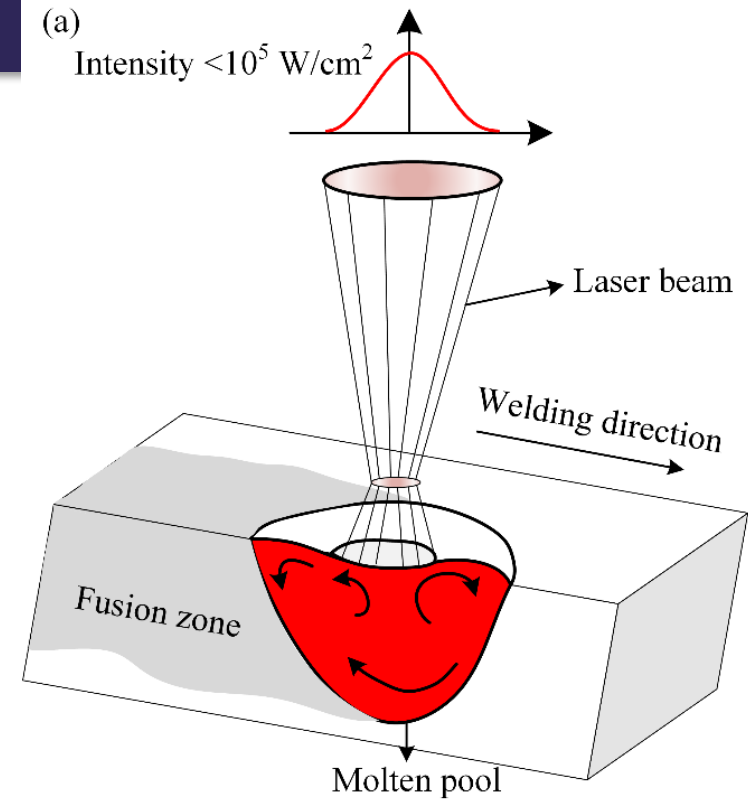
Keyhole mode of Welding



Modes of Welding: Conduction mode of welding

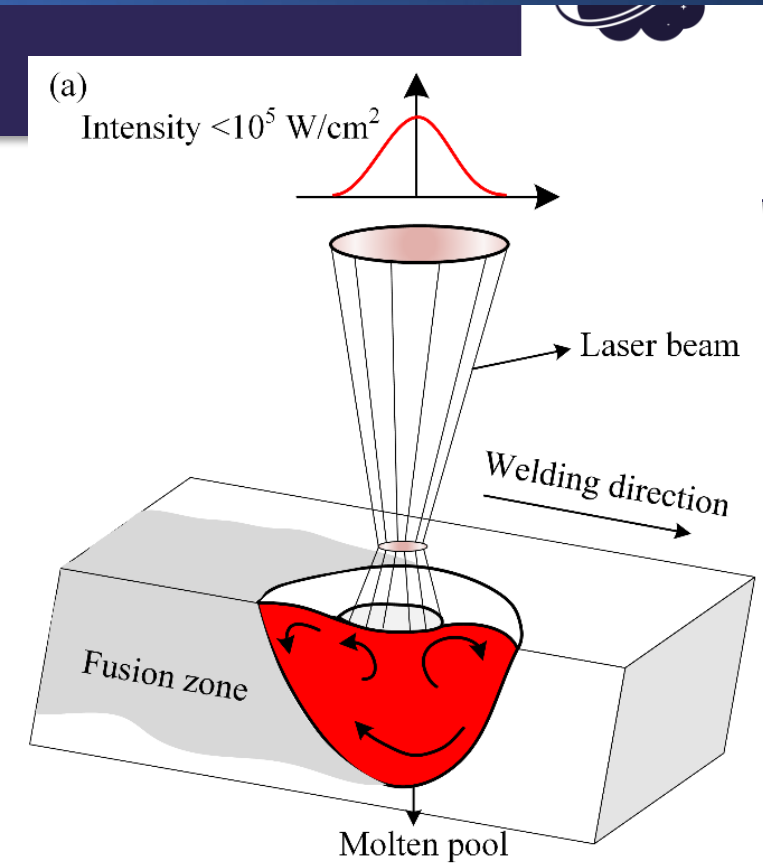


- Conduction weld regime takes place when the power density is below approximately 10^5 W/cm^2 yet remains sufficiently high to melt the base material.
- To achieve a lower power density, one approach is to defocus the beam, which consequently enlarges the incident laser beam spot size on the base material as illustrated in Figure.
- The power density in this mode is not high enough to vaporise the material and form a keyhole in the base metal.
- Instead, the laser beam's energy is absorbed at the surface of the workpiece and is conducted into the bulk of the material.
- It results in a broad heat distribution, similar to that of arc welding process. This mode provides precise control during the welding process and allows for accurate control of weld depth and shape resulting in a smooth and rounded weld seam.



Modes of Welding: Conduction mode of welding

- Welds produced in conduction mode typically exhibit a depth-to-width ratio of less than 0.5 with a shallow penetration depth, and a hemispherical weld profile.
- The weld penetration depth is limited by the thermal conductivity of the material being welded, so deep penetration is less probable.
- Conduction welding is known for its relative stability, facilitating the production of high-quality welds with minimal defects such as hot cracking and porosity.
- However, this process involves higher heat input, which can lead to deterioration of mechanical properties, the formation of wider fusion zone (FZ) and heat affected zones (HAZ), and increased distortions in the base metal.
- Consequently, heat conduction limited laser beam welding is primarily utilised for applications such as spot welding, seam welding and laser cladding

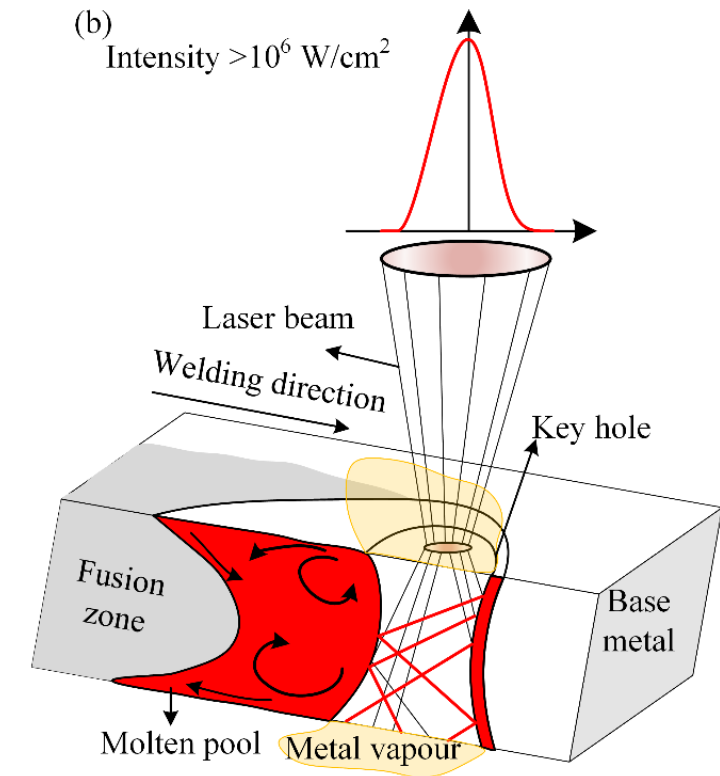


Modes of Welding: Keyhole mode of welding

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Keyhole mode of Welding

- During welding, the vapour pressure generated from the weld pool expels molten metal creating a continuous, deep and narrow cavity known as keyhole.
- This keyhole formation occurs in a weld regime operating with a power density exceeding 10^6 W/cm^2 , sufficient to vaporise the base material to plasma and maintain the keyhole as depicted in Figure.
- Furthermore, significant amounts of heat are dissipated by conduction along the keyhole wall in radial direction surrounded by molten metal.
- The presence of plasma permits the incident laser beam to penetrate the keyhole and heating the material not just at the top surface but throughout its thickness of the base metal, therefore, the formation of metal vapour is enhanced.
- Once the keyhole is established, the laser beam's coupling to the base metal increases significantly, with absorptivity climbing from around 10% to approximately 65%, owing to the multiple reflections at the keyhole walls, where the beam energy is repeatedly reflected until it either escapes or is entirely absorbed through Fresnel absorption.

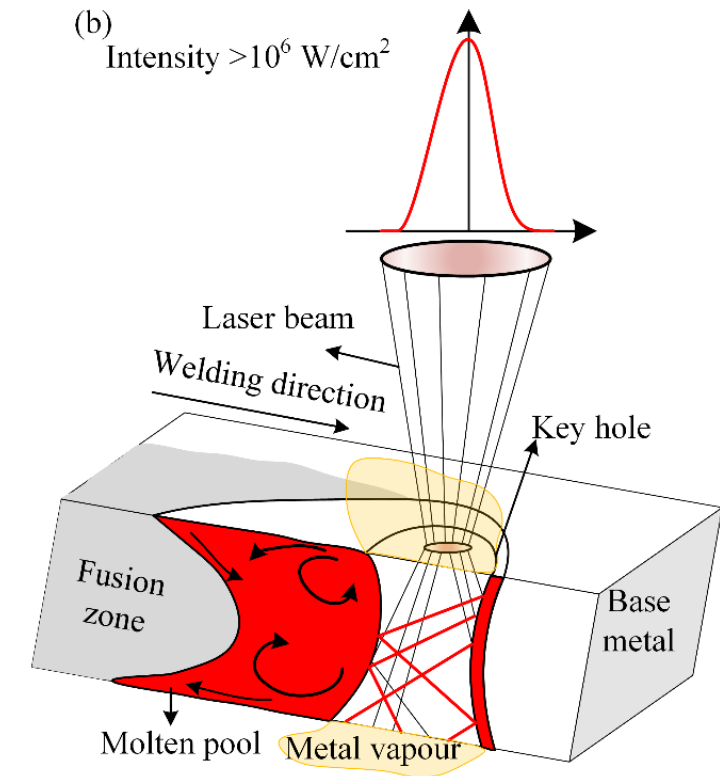


Modes of Welding: Keyhole mode of welding

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Keyhole mode of Welding

- The Fresnel absorption refers partial reflection and absorption of incident light on an opaque surface, it is dependent upon the angle of incidence between the laser beam and the keyhole wall and the wavelength of the laser beam.
- By traversing this high intensity laser beam relative to the base metal, a narrow weld bead with a high aspect ratio is produced. The heat affected zone (HAZ) in keyhole mode is notably narrow and runs parallel to the weld bead.
- A primary benefit of using a keyhole mode laser welding is its capability to weld at high speeds along with deep penetration.
- Furthermore, the localised heating leads to a smaller HAZ which is beneficial for maintaining the base material's properties. Materials with higher reflectivity, such as aluminium alloys, are effectively welded in this mode due to the increased laser absorption during the keyhole formation.

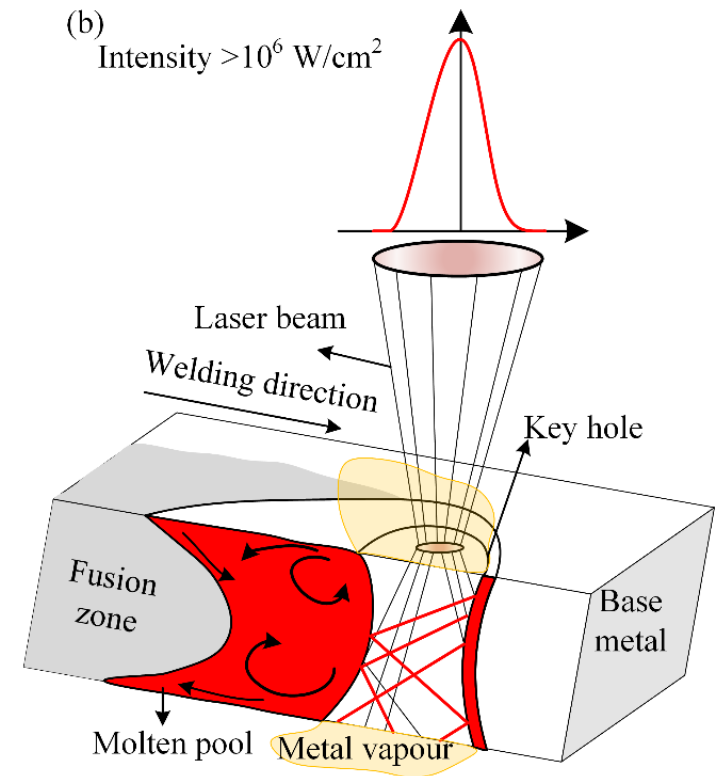


Modes of Welding: Keyhole mode of welding

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Keyhole mode of Welding

- However, the high-power density of the keyhole mode can lead to challenges, including increased porosity, spatter and potential instability of the keyhole.
- Control over the molten pool shape, and penetration depth is also less compared to conduction mode welding.
- Despite these challenges, keyhole mode laser welding excels at providing high-speed, deep penetration welds with minimal distortion but requires more sophisticated and costly equipment and can be more sensitive to parameters and materials properties compared to the conduction mode welding



Mechanism



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- In "keyhole" welding in which there is sufficient energy/unit length to cause evaporation and hence a hole in the melt pool
- This hole is stabilized by the pressure from the vapor being generated
- In some high powered plasma welds there is an apparent hole, but this is mainly due to gas pressures from the plasma or cathode jet rather than from evaporation
- The "keyhole" behaves like an optical black body in that the radiation enters the hole and is subject to multiple reflections before being able to escape
- Nearly all the beam energy is absorbed once the keyhole is formed
- This can be both a blessing and a nuisance when welding high reflectivity materials
 - Reasonably power is needed to start the "keyhole"
 - as soon as the keyhole has started then the absorptivity jumps from 3% to 98% which could potentially damage the weld structure

Mechanism

Two principle areas of interest:

–Flow structures which directly affects the wave formation in the weld pool and frozen bead geometry

–Absorption mechanism

- Fresnel absorption (absorption during reflection from surface)

- Inverse plasma re-radiation

–It affects

- Flow stability

- Entrapped porosity

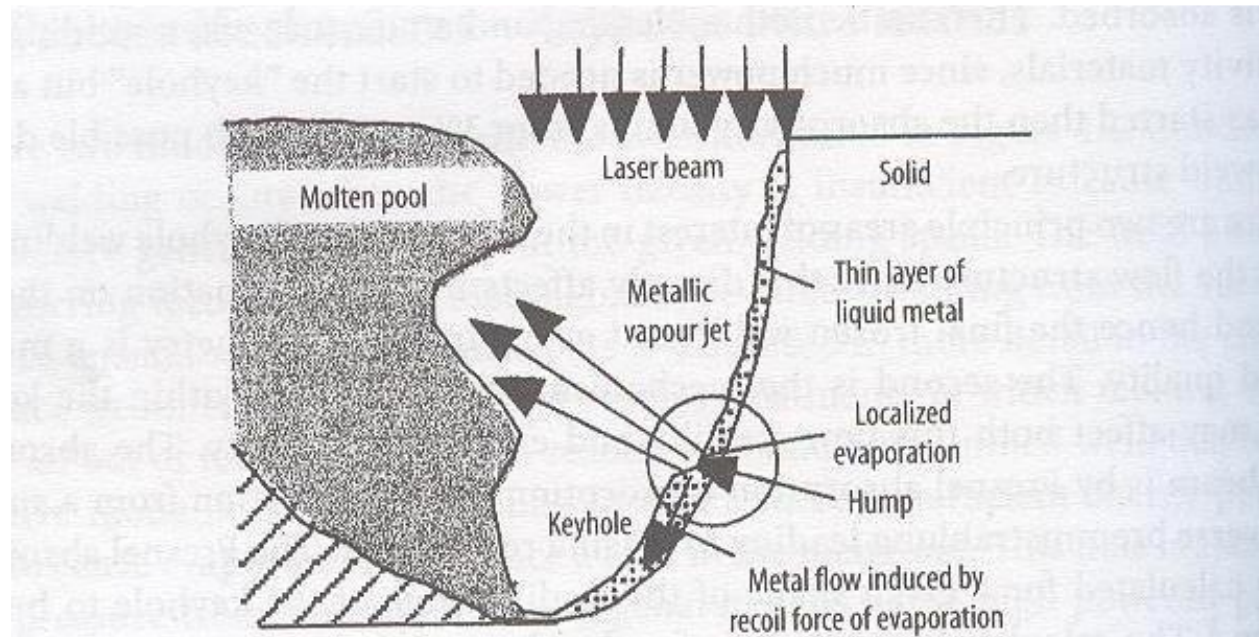


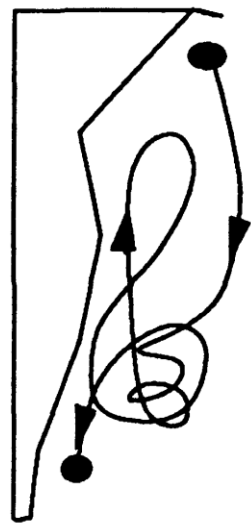
Figure 4.6 Side view illustration of the keyhole shape and beam absorption.³

Mechanism



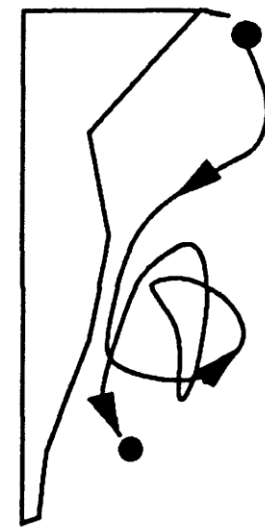
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Keyhole



Melt pool

Keyhole



Start

Melt pool

Finish

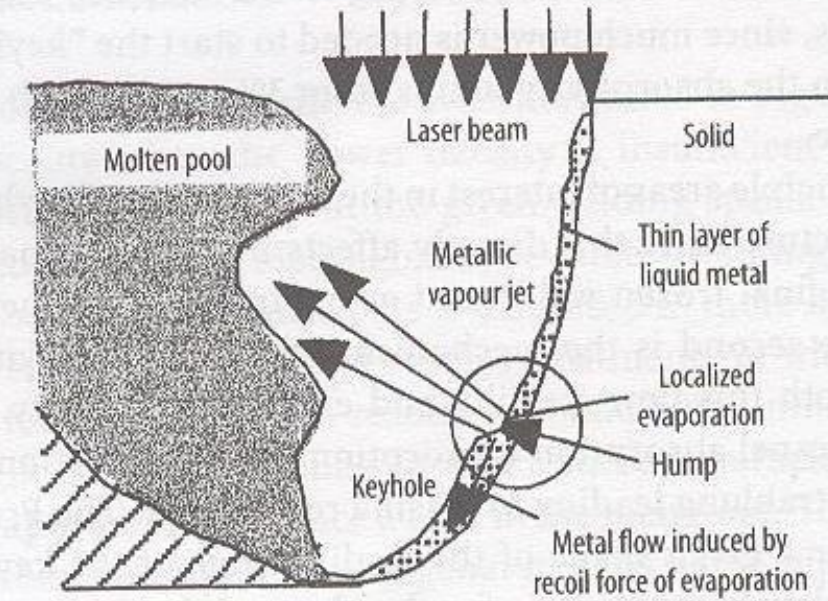


Figure 4.6 Side view illustration of the keyhole shape and beam absorption.³

Keyhole Shape and Absorption

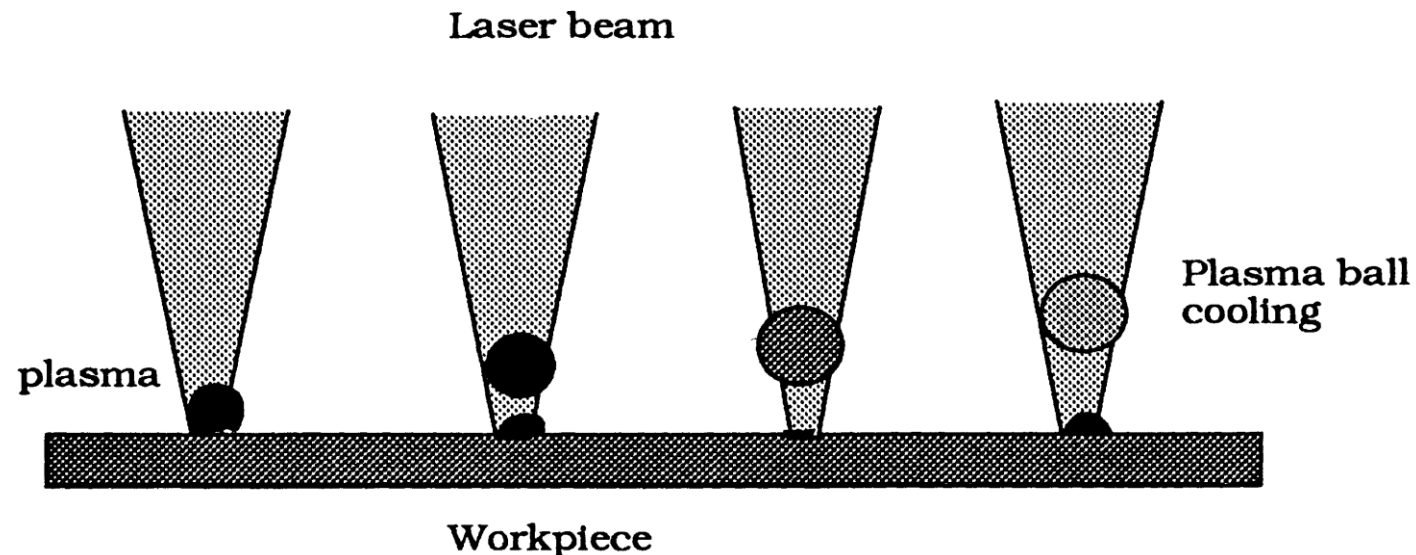


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- The keyhole walls are fluctuating with flow velocities up to 0.4 m/s
- The thin melt on the leading edge flows downward with fluctuations as in a wave
- Any hump on the surface will cause localized higher absorption and an explosion due to instantaneous evaporation
- This sends a vapor jet through the rear molten pool causing stirring and bubble entrapment
- The usual flow in molten pool has vortex

Plasma Blocking

- The keyhole contains considerable metal vapor, which is partially absorbing and hence capable of forming a plasma on further heating
- This hot plasma vapor emerging from the keyhole may ionize the shroud gas.
- Ionized gas has free electrons and is thus capable of absorbing or even blocking the beam.
- If there is no gas to blow the plasma away the plasma is formed intermittently due to the "blocking" of the beam.
- Mechanism is debatable:
 - whether plasma is opaque enough at the temperatures measured to block the beam
 - or the effect just noted is due to the plasma scattering the beam by variations in refractive index



Plasma Blocking



Beam Properties:

- Power, pulsed or continuous
- Spot size and mode
- Polarisation
- Wavelength

Transport Properties:

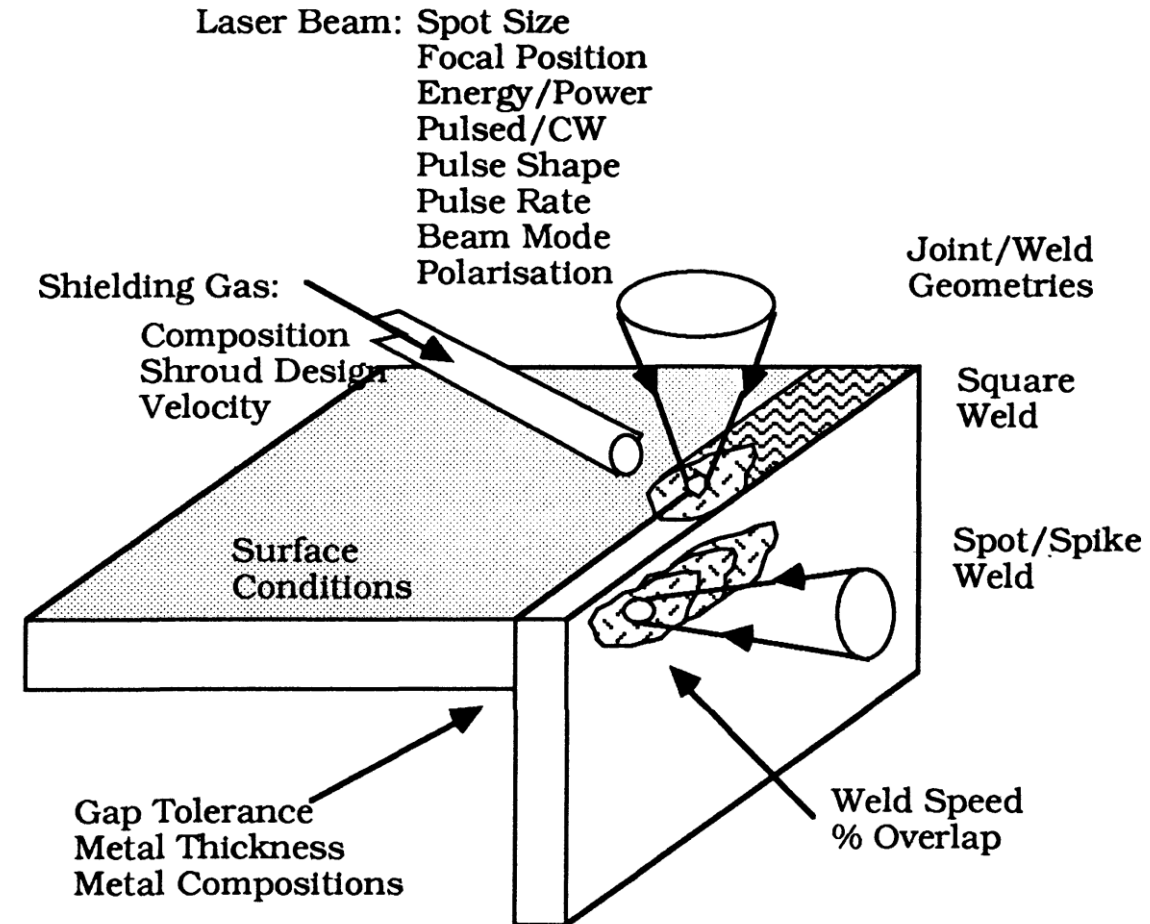
- Speed
- Focal position
- Joint geometries
- Gap tolerance

Shroud Gas Properties:

- Composition
- Shroud design
- Pressure/velocity

Material Properties:

- Composition
- Surface condition



Plasma Blocking



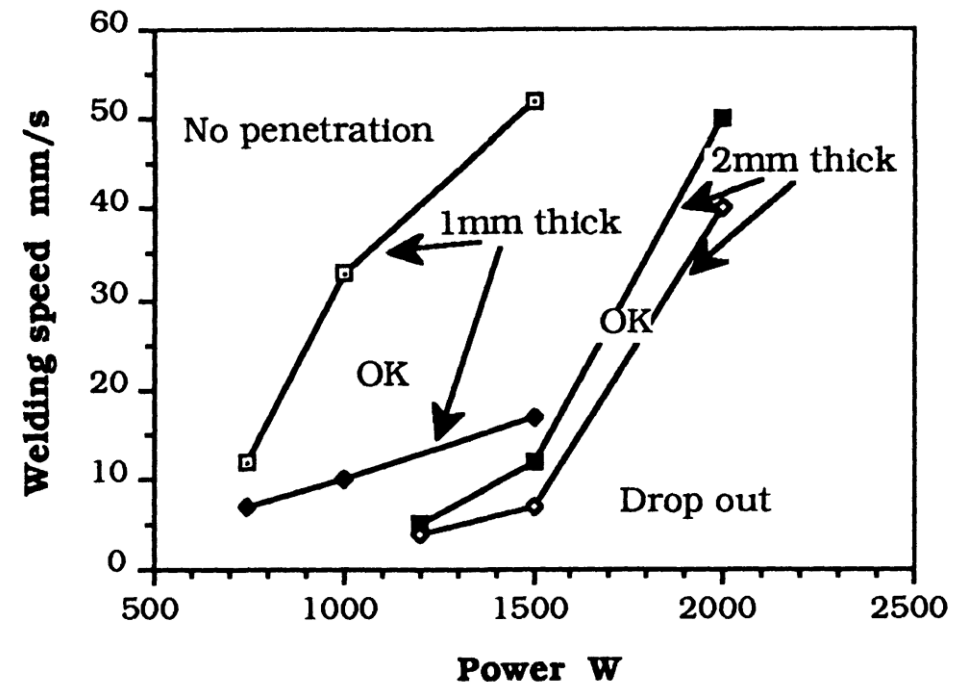
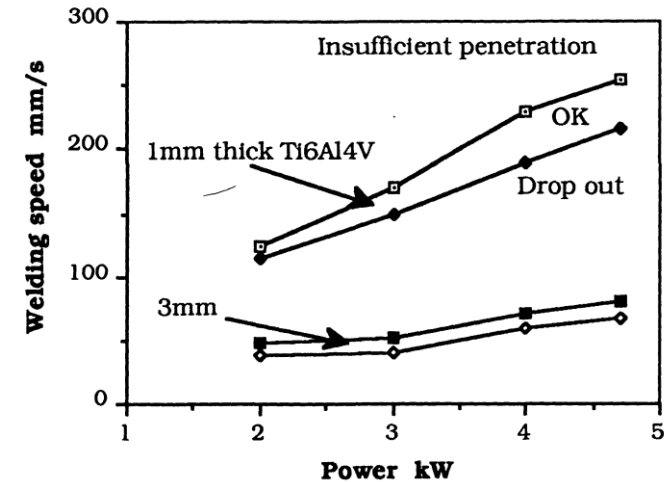
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There are two main problems in welding:

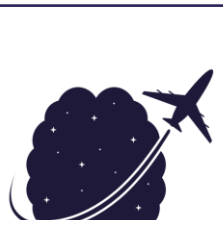
- lack of penetration
- or the inverse, "drop out".

- These are the boundaries for a good weld for a given power
- The maximum welding speed for a given thickness rises with increase in power
- The fall off shown at the higher power levels of 2kW could be attributed to the poorer mode structure given by most lasers when working at their peak power

For higher powers the operating window is larger



Forces during Keyhole Welding

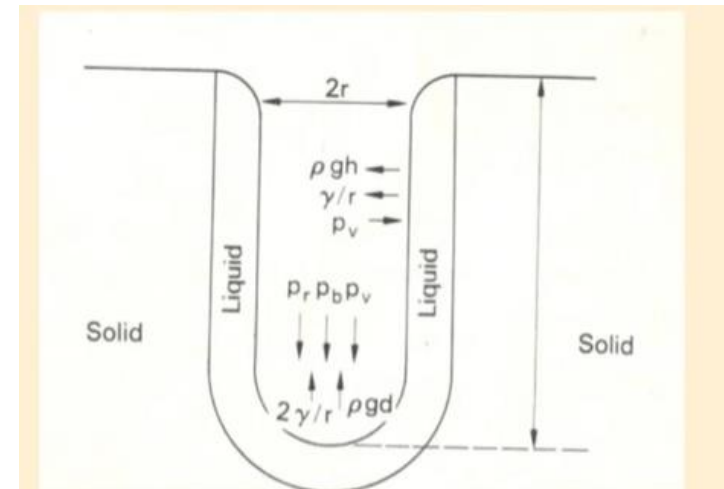
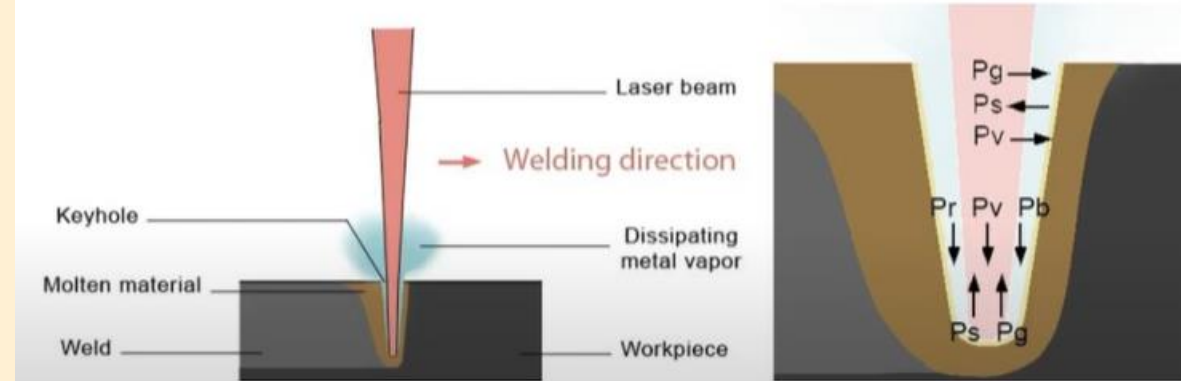


Forces aid keyhole

- Beam pressure (P_b)
- Vapour pressure (P_v)
- Recoil pressure (P_r)

Forces close the keyhole

- Gravitational pressure (ρgh)
- Surface tension pressure (P_γ)



At the bottom of the closed hemispherical keyhole

$$P_b + P_v + P_r = \frac{2\gamma}{r} + \rho gh$$

Direct Heat



During direct heating,

- heat flow is governed by classical thermal conduction from a surface heat source and the weld is made by melting portions of the base material

- The first conduction welds were made in the early 1960s, used low power pulsed ruby and CO₂ lasers for wire connectors

- Conduction welds can be made in a wide range of metals and alloys in the form of wires and thin sheets in various configurations using

- CO₂ , Nd:YAG and diode lasers with power levels on the order of tens of watts

- Direct heating by a CO₂ laser beam can also be used for lap and butt welds in polymer sheets

Transmission Welding



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Transmission welding is an efficient means of joining polymers that transmit the near infrared radiation of Nd:YAG and diode lasers

- Composites can be joined provided that the thermal properties of the matrix and reinforcement are similar.
- The energy transmission mode of conduction welding is used with materials that transmit near infrared radiation, notably polymers
- An absorbing ink is placed at the interface of a lap joint. The ink absorbs the laser beam energy, which is conducted into a limited thickness of surrounding material to form a molten interfacial film that solidifies as the welded joint
- Thick section lap joints can be made without melting the outer surfaces of the joint
- Butt welds can be made by directing the energy towards the joint line at an angle through material at one side of the joint, or from one end if the material is highly transmissive

Pulsed Power



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The use of pulsed power allows two more variables:

- pulse repetition frequency (PRF),
- % overlap to be considered.

- The welding speed is decided by :

- spot size x PRF x (1-% overlap).

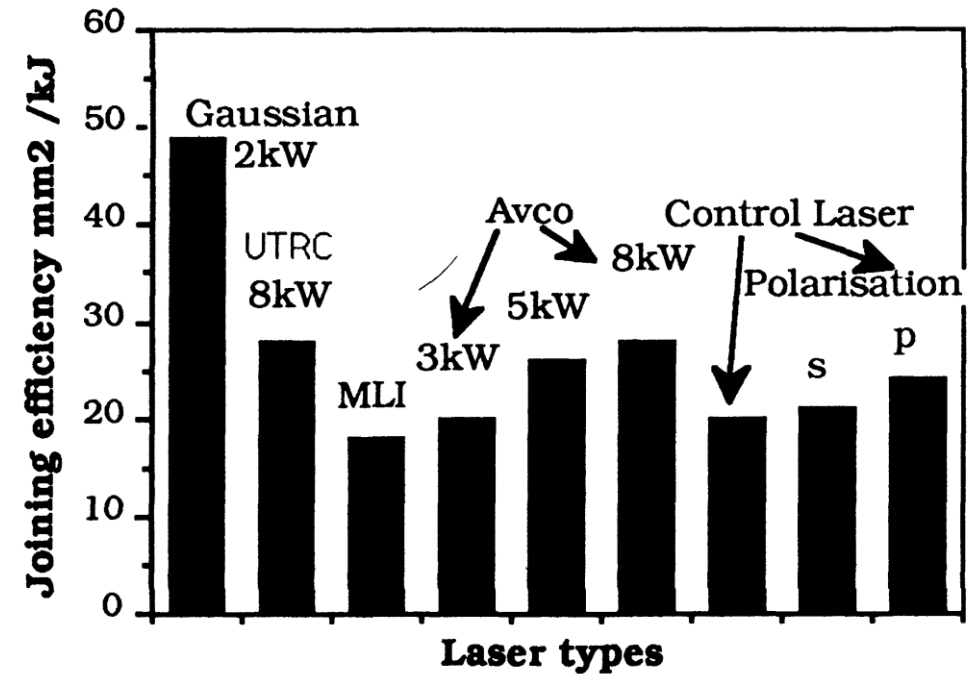
- Speed is independent of power.

- Penetration is a function of power and likewise the weld bead quality.

- Too much power causes vaporization and material ejection as in drilling
- Thus, for welding the pulse is usually longer than for drilling and shaped to have a smaller initial peak.

Joining Efficiency

- The joining efficiency is greatly affected by the mode as illustrated by various researchers



Penetration Laser Welding and Laser Welding Efficiency

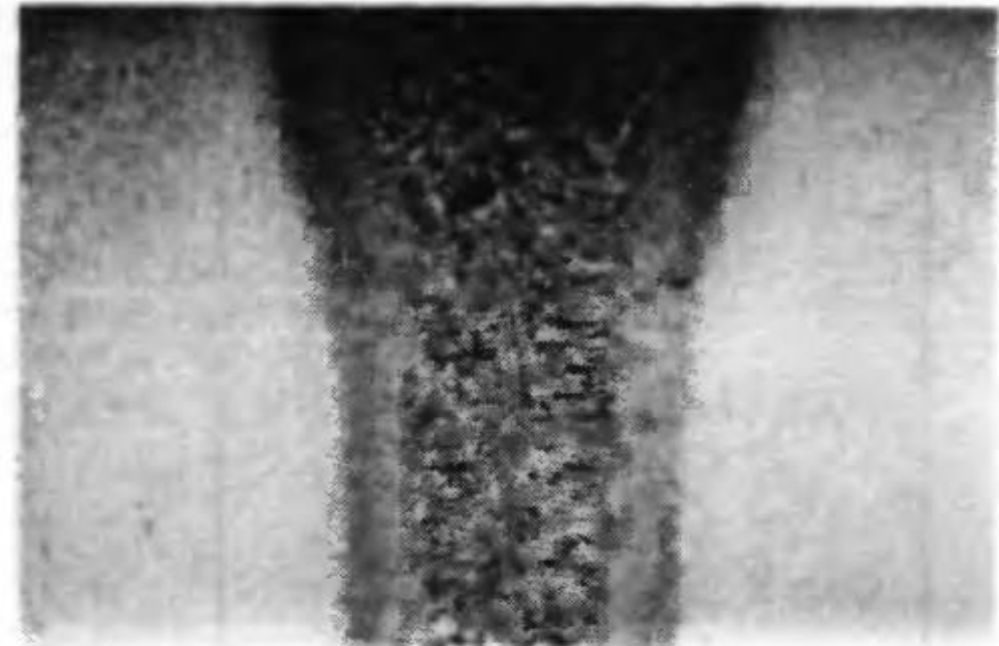


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At high power densities all materials will evaporate if the energy can be absorbed. Thus, when welding in this way a hole is usually formed by evaporation

- This "hole" is then traversed through the material with the molten walls sealing up behind it
- The result is what is known as a "keyhole weld. This is characterized by its parallel sided fusion zone and narrow width

- A term to define this concept of efficiency is known as the "joining efficiency"
- The joining efficiency is not a true efficiency in that it has units of (mm²joined /kJ supplied)
- – Efficiency= $V \cdot t / P$ (the reciprocal of the specific energy in cutting) where V = traverse speed, mm/s; t = thickness welded, mm; P = incident power, kW.



Comparison



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Table 4.1 Relative Power Densities of Different Welding Processes		
Process	Heat Source Intensity W/cm^2	Fusion zone profile
Flux Shielded Arc Welding	$5 \times 10^6 - 10^8$	
Gas Shielded Arc Welding	$5 \times 10^6 - 10^8$	 low
		 high
Plasma	$5 \times 10^6 - 10^{10}$	 low
		 high
Laser or Electron Beam	$10^{10} - 10^{12}$	 defocus
		 focus

Joining Efficiency

The higher the value of the joining efficiency the less energy is spent in unnecessary heating

–Lower heat affected zone (HAZ)

–Lower distortion

- Resistance welding is most efficient in this respect because the fusion and HAZ energy is only generated at the high resistance interface to be welded
- Laser and electron beam also have good efficiencies and high power densities

Table 4.2 Relative Joining Efficiencies of Different Welding Processes	
Process	Approximate Joining Efficiency mm ² /kJ
Oxy Acetylene Flame	0.2 - 0.5
Manual Metal Arc (MMA)	2 - 3
Tungsten Inert Gas (TIG)	0.8 - 2
Submerged Arc Welding (SAW)	4 - 10
High Frequency Resistance Welding	65 - 100
Electron Beam (EB)	20 - 30
Laser	15 - 25

Advantages of Laser Welding



Advantages of Laser Welding:

- Microstructural degradation is the minimum and narrow heat-affected zone (HAZ) width and low distortion, as compared to conventional arc welding, due to the low heat input to the workpiece.
- It has the ability to achieve a high depth-to-width ratio of welds which eliminates the need for multipass welds as done in arc welding.
- Laser welding is a high-precision welding technique with high speed and flexibility with the ability to weld difficult to weld materials such as titanium, copper etc.
- It does not require filler materials and can be done at room temperature by producing welds with little or no contamination at all.
- It can weld dissimilar materials and can be automated by using robotic arms.

Limitations of Laser Welding

Limitations of Laser Welding:



- The typical spot size of the laser beam is between 100 to 1000 μm which requires stringent positioning of the parts with allowable gaps around 0.1 times the thickness of the material.
- When welding at high speeds, the rapid solidification and cooling rates increased the chances of pore and crack formation within the weld.
- The rapid cooling rate of the order of 4000 K/sec can lead to an increase in the hardness of HAZ and weld zone and deteriorate the toughness of the welds.
- One of the major limitations of laser welding is against materials with high reflectivity such as aluminium, copper etc. where the loss of power is more than 70% of the power input.
- Utilizing laser beams with high-power density gives rise to the creation of an exceedingly unstable molten pool, increasing the likelihood of spatter formation.
- High equipment cost
- Safety concern and require protective measures

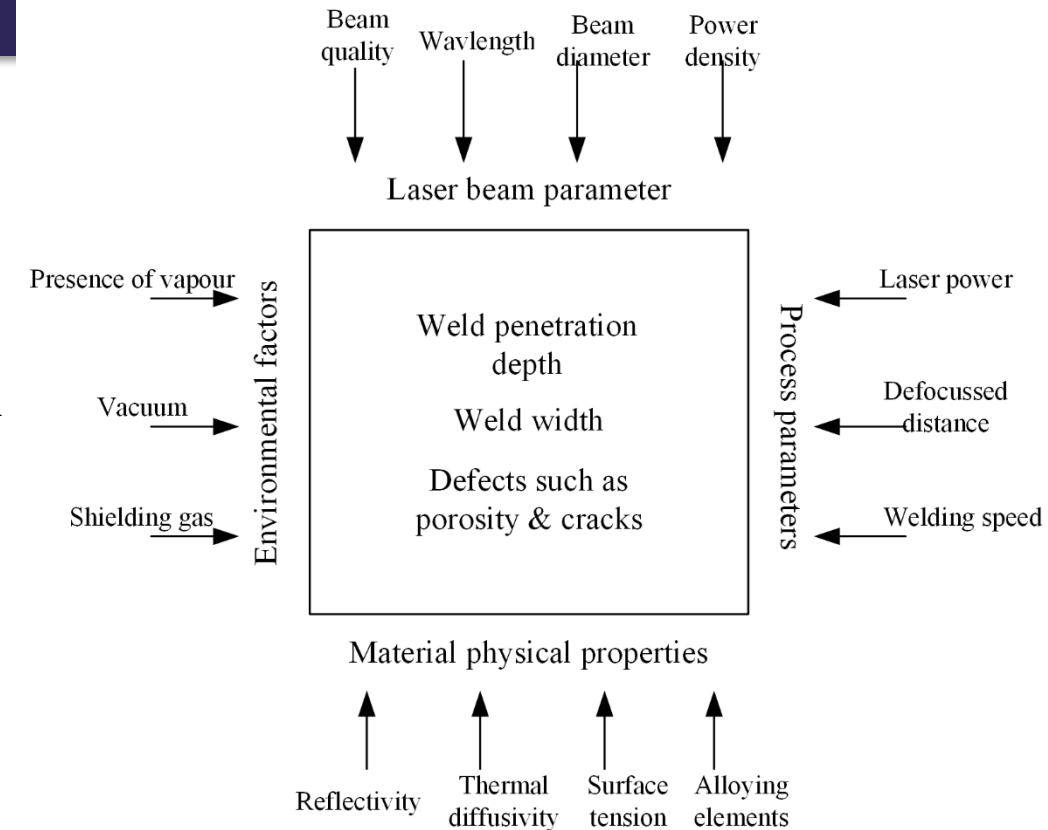
Laser Welding Parameters

Laser beam parameter

The laser beam parameters which in wavelength such as IR (1080 nm), green (520 nm) and blue (450 nm) laser, influencing the welding process. For example, the absorption of laser energy in copper improves with shorter wavelengths significantly affecting penetration depth. Additionally, the beam quality and the beam diameter including the type of TEM₀₀ (Transverse electromagnetic mode) which is the Gaussian beam distribution, significantly impacts the focus and thus the weld geometry

Laser power

The focussed intensity can be altered with laser power, which has a direct correlation with the depth of penetration and weld width, where increased laser power typically results in deeper weld penetration. However, an excess power level can induce defects such as cracks, porosity and undercutting. Conversely, a lower laser power results in reduced penetration depth and narrower welds and may also lead to lack of fusion.



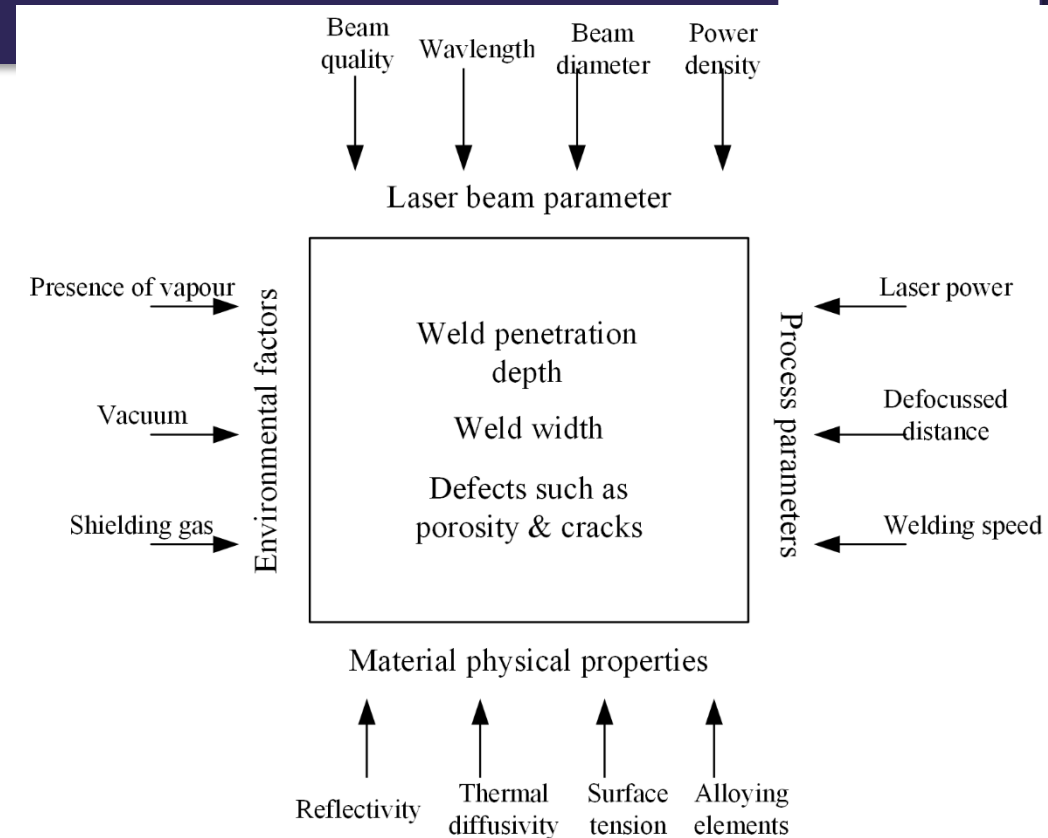
Laser Welding Parameters

Focal distance

The laser beam intensity can also be altered by defocussing and changing the angle of incidence of the laser beam with the material surface, attributed to this, the heat input can be utilised to alter the desired weld geometry and quality. With smaller beam diameter it can lead to higher power density with increasing penetration depth and width of the weld zone.

Welding Speed

The laser welding speed influences the effective heat transfer, with higher speeds can result in narrower and heat-affected zones (HAZ) in the fusion zone. This can lead to rapid cooling rates and finer microstructures. Whereas slower welding speeds, increase heat input, widens the HAZ and can cause coarse grain growth and change the fusion zone strength



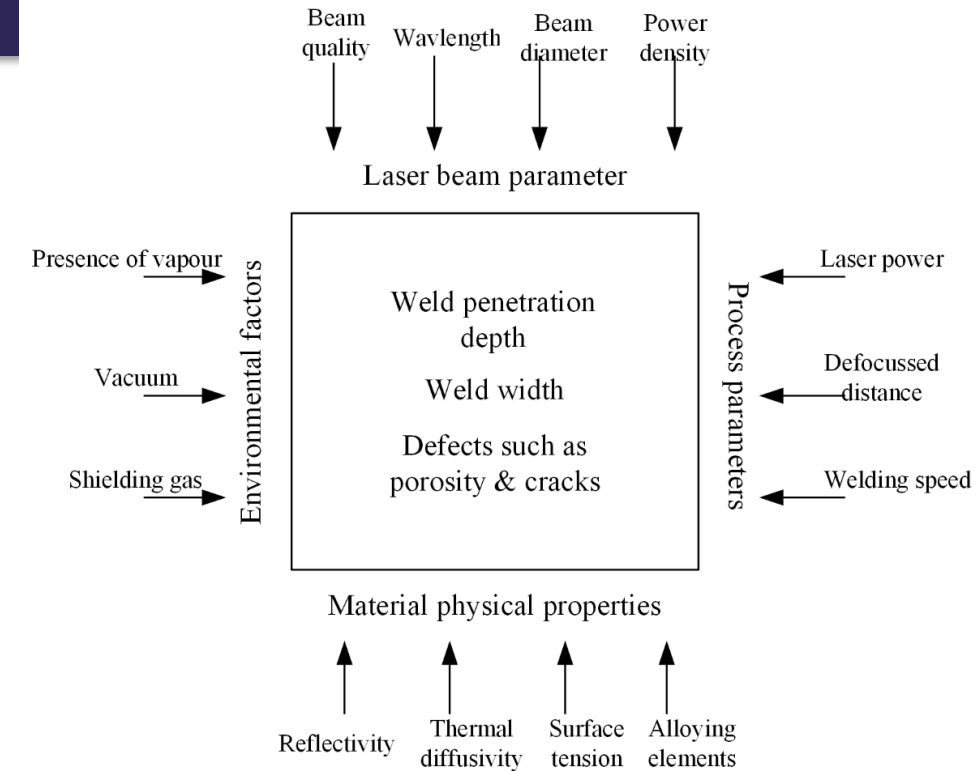
Laser Welding Parameters

Material physical properties

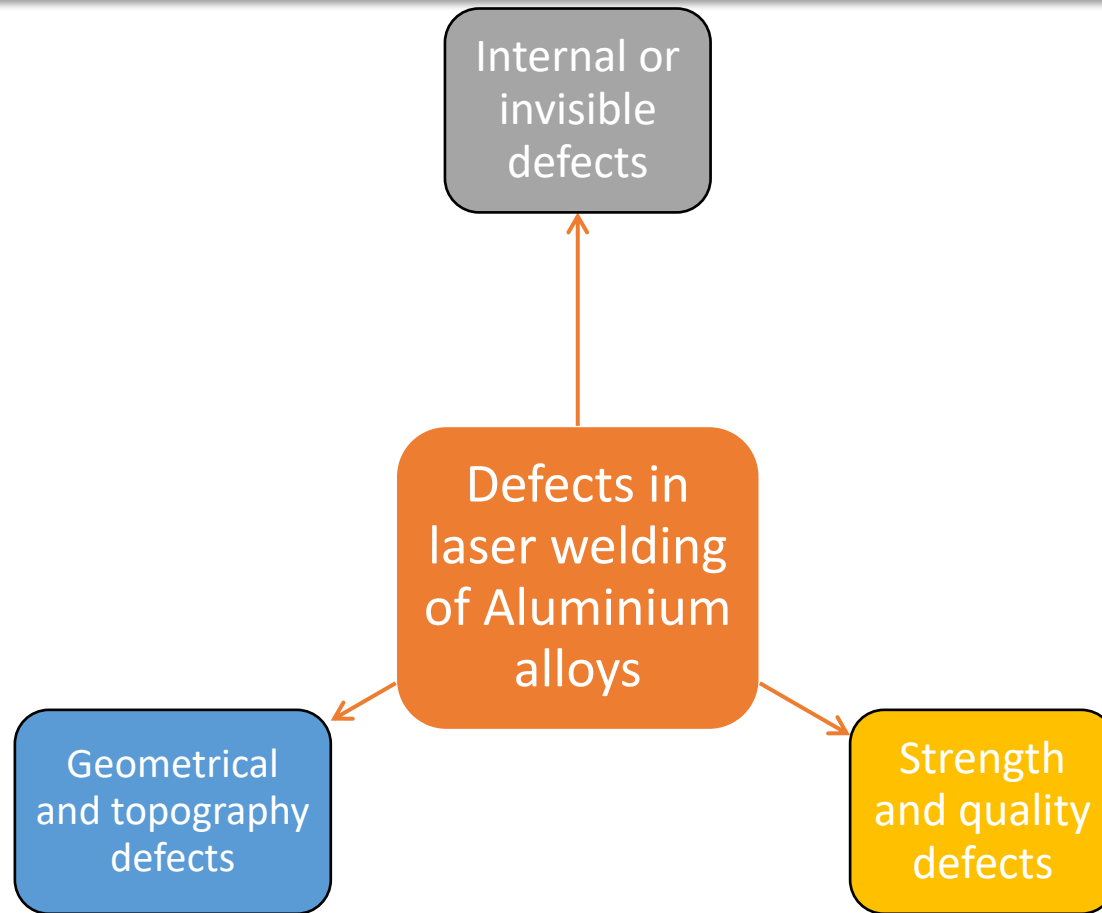
- Material physical properties are crucial factors, such as laser beam reflectivity, thermal diffusivity, surface tension and the presence of volatile alloying elements in the base material being welded significantly affect the weld quality by increasing the thermal stresses and may lead to cracks.
- Furthermore, initial base metal microstructure and its phase composition can also influence heat distribution and final weld microstructure and properties

Environmental factors

- Environmental conditions including the surrounding air or vacuum, the use of shielding gas, and the gas flow rate also play pivotal roles by stabilising the keyhole and molten pool during welding.
- Additionally, the interaction of the laser beam with the material can lead to plasma, affecting the energy absorption and distribution during the welding process which can attribute to the increased spatters and other defects.



Defect formation during laser welding aluminium alloys

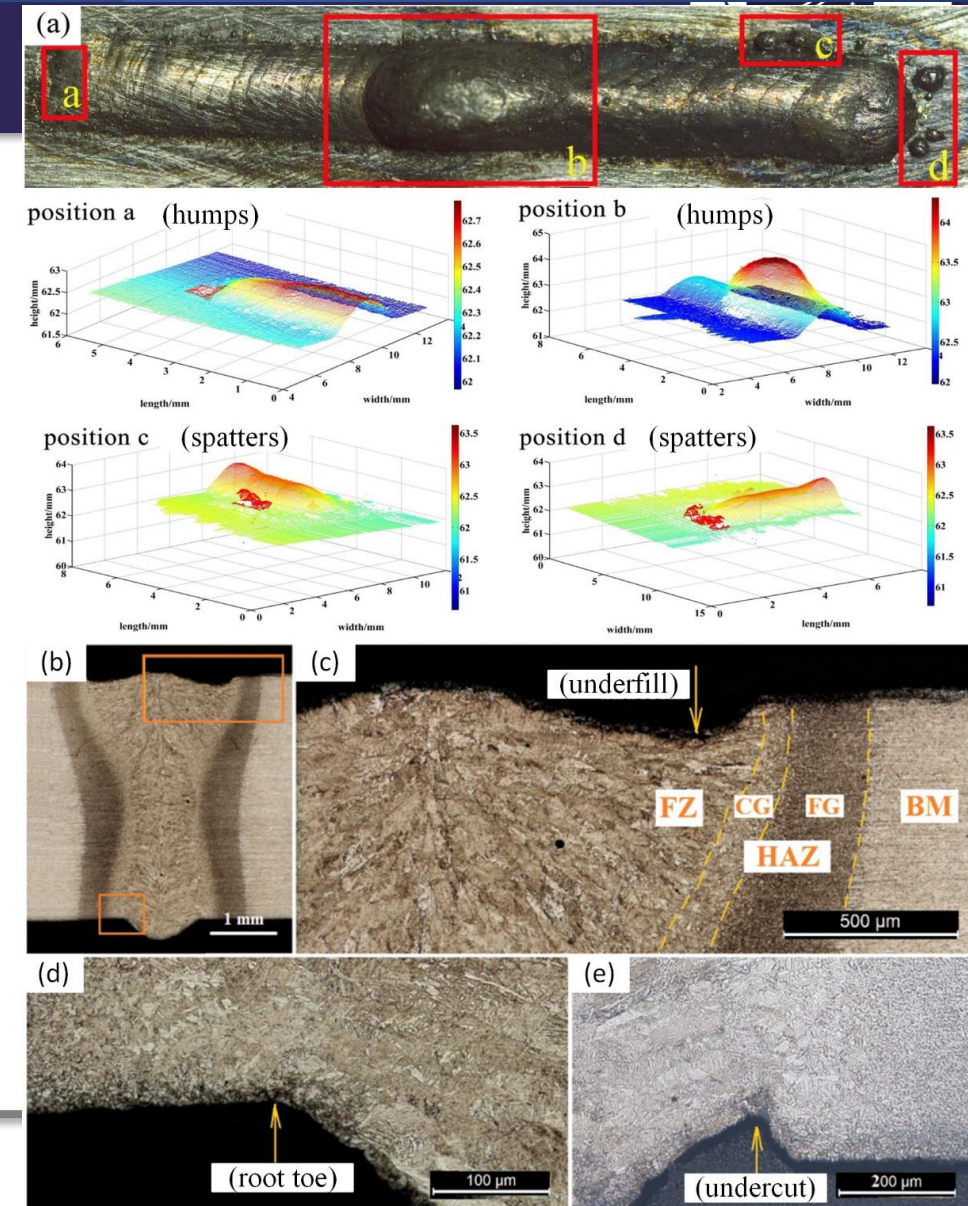


Achieving defect-free welds in aluminium alloys using the remote laser welding demands a meticulous adjustment of the above-mentioned laser parameters, analysing the environmental conditions and an understanding of the material's properties, tailored to the specific requirements of the alloy composition. In laser welding of aluminium alloys, defects can be categorically divided into three distinct groups: (i) geometrical and topography defects, (ii) strength and quality defects, and (iii) internal or invisible defects

Defect formation during laser welding aluminium alloys

Geometrical and topography defects

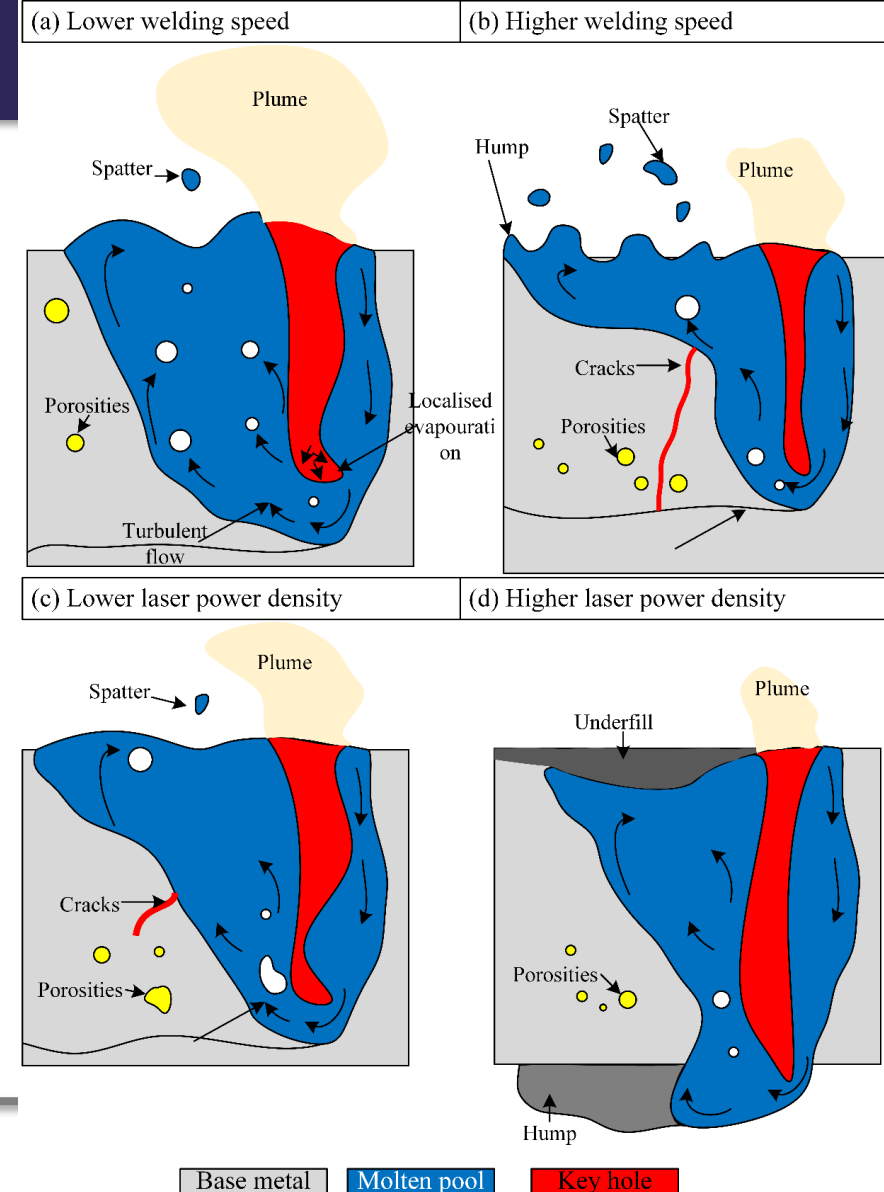
- During laser welding, aluminium alloys undergo a series of thermal cycles, which includes a series of heating, melting, vaporisation, solidification and cooling of base metal and they are inevitably accompanied by volume changes due to thermal expansion and contraction resulting in various defects such as distortion or deformation, residual stresses, or even cracking defects within the joint.
- Owing to the higher overall heat input during laser welding can lead to an enhanced molten pool, and a significant difference between upper and lower bead widths, causes angular deformation or contraction defects in aluminium sheets.
- Topography defects such as **spatters**, **humps**, **underfills**, and **undercuts** are frequently observed on the **top surface welded joint**.



Defect formation during laser welding aluminium alloys

Geometrical and topography defects

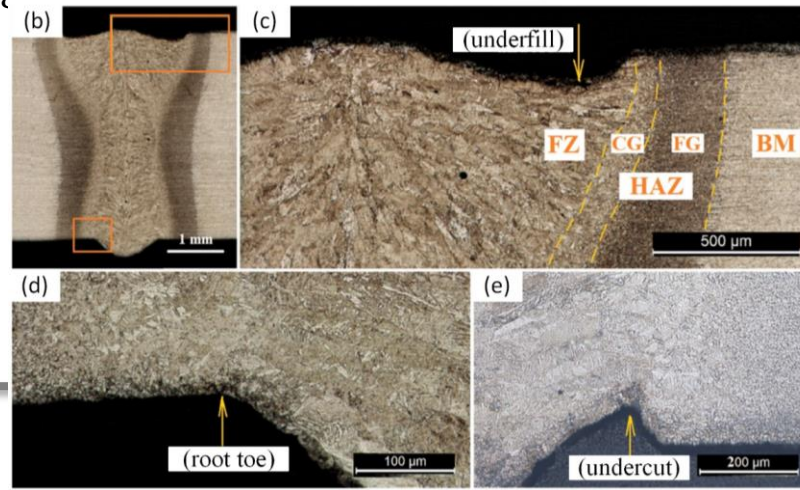
- **Spattering**, in particular results from the formation of metal droplets ejected from the turbulent molten pool, a phenomenon intensified by the plume's dynamic conditions within the keyhole.
- The ejection of droplets from the weld seam results in material deficit, thereby compromising mechanical properties and probably lead to underfill and irregular pit defects within the fusion zone.
- Further, the tendency of the molten pool to form a concave bead and convex bottom surface during welding can be due to the lower surface tension of aluminium alloys at higher laser power density.
- The molten material at lower temperatures near the bottom rear end of the molten pool, which typically contains a lower oxygen content, exhibits a high surface tension, and is strong enough to draw the higher temperature liquid near the keyhole's tip, culminating in the formation of bottom humps.



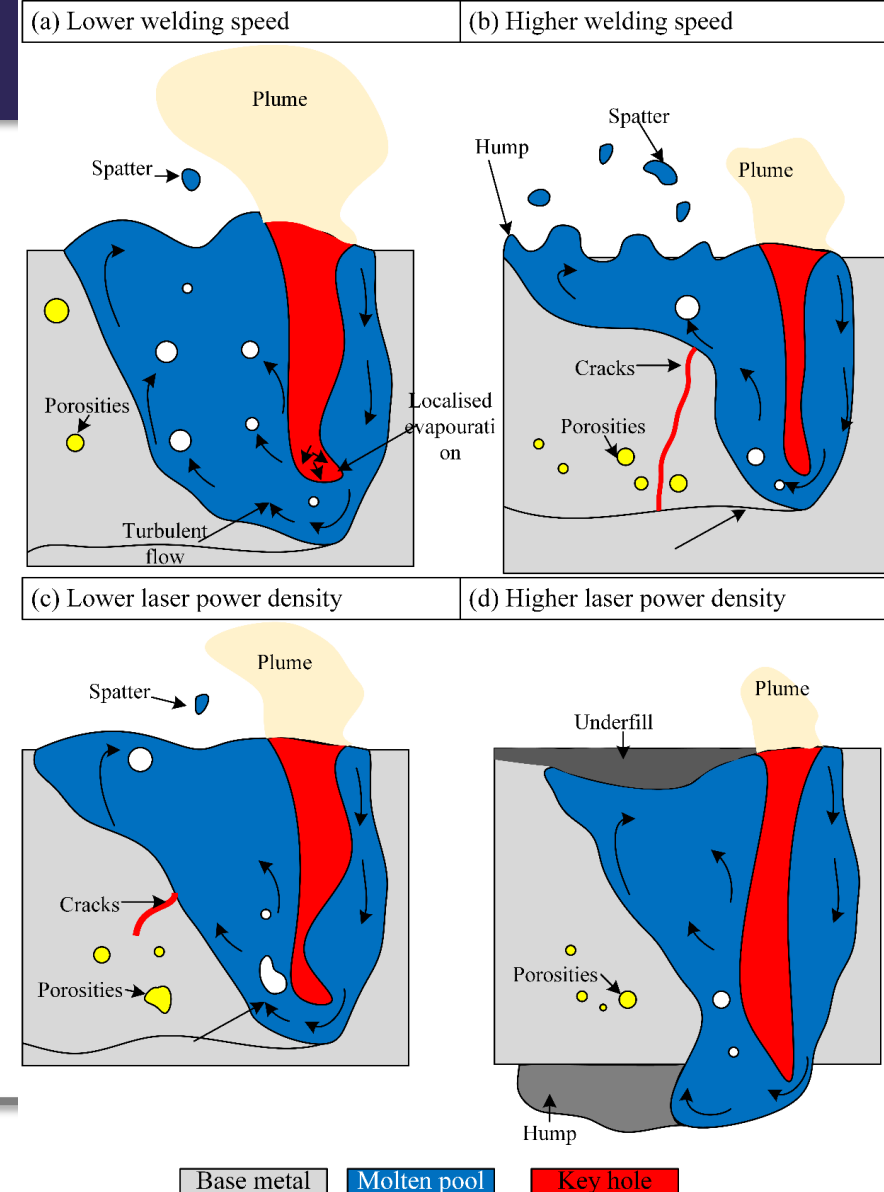
Defect formation during laser welding aluminium alloys

Geometrical and topography defects

- An **undercut** defect, identified by a groove along the toe end of the weld bead, typically arises in conditions of elevated laser power density, high pressure from assist gas or extensive flow of shielding gas from the front side of welding process.
- Furthermore, the defect of **underfilling** and **humping** occur under similar conditions of higher laser power density.
- These defects manifest as periodic concave top surface and convex bottom surface under a narrow weld bead. Also, the formation of surface humps is caused by the backward flow of molten metal, driven by plume explosions and intensified by the higher surface tension of the molten metal within a narrow molten pool.



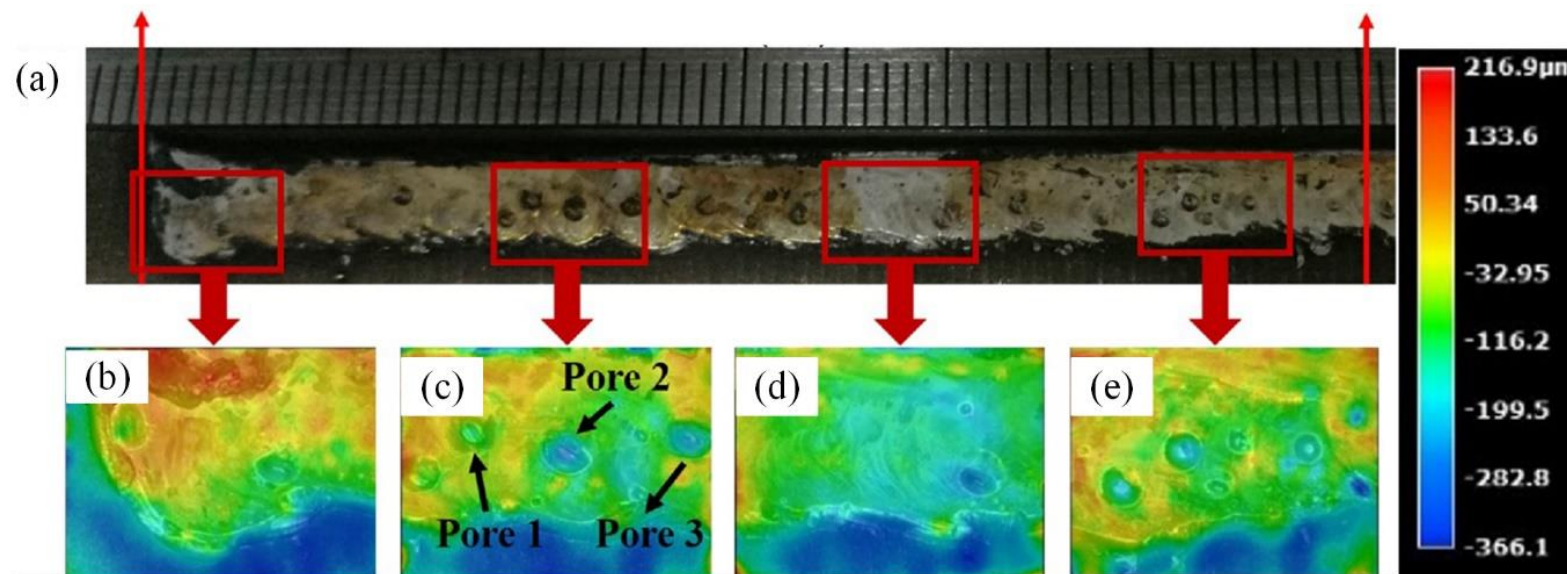
Pamarthi et al Static Laser Beam Shaping to Tailor the Microstructure and Mitigate Cracking Susceptibility in Autogenous Laser Welded 6xxx Aluminium Alloys



Defect formation during laser welding aluminium alloys

Strength and Quality defects

- When subjected to welding conditions, aluminium structure often exhibits defects that become evident through the local response of the weld and the heat-affected zone (HAZ) material under tensile load.
- Owing to the quality, the strengths of the joints are slightly to significantly lower than those of the base alloys. The reduction in strength and strain during the tensile testing is attributed to the formation of weld defects and the formation of pores in the joint

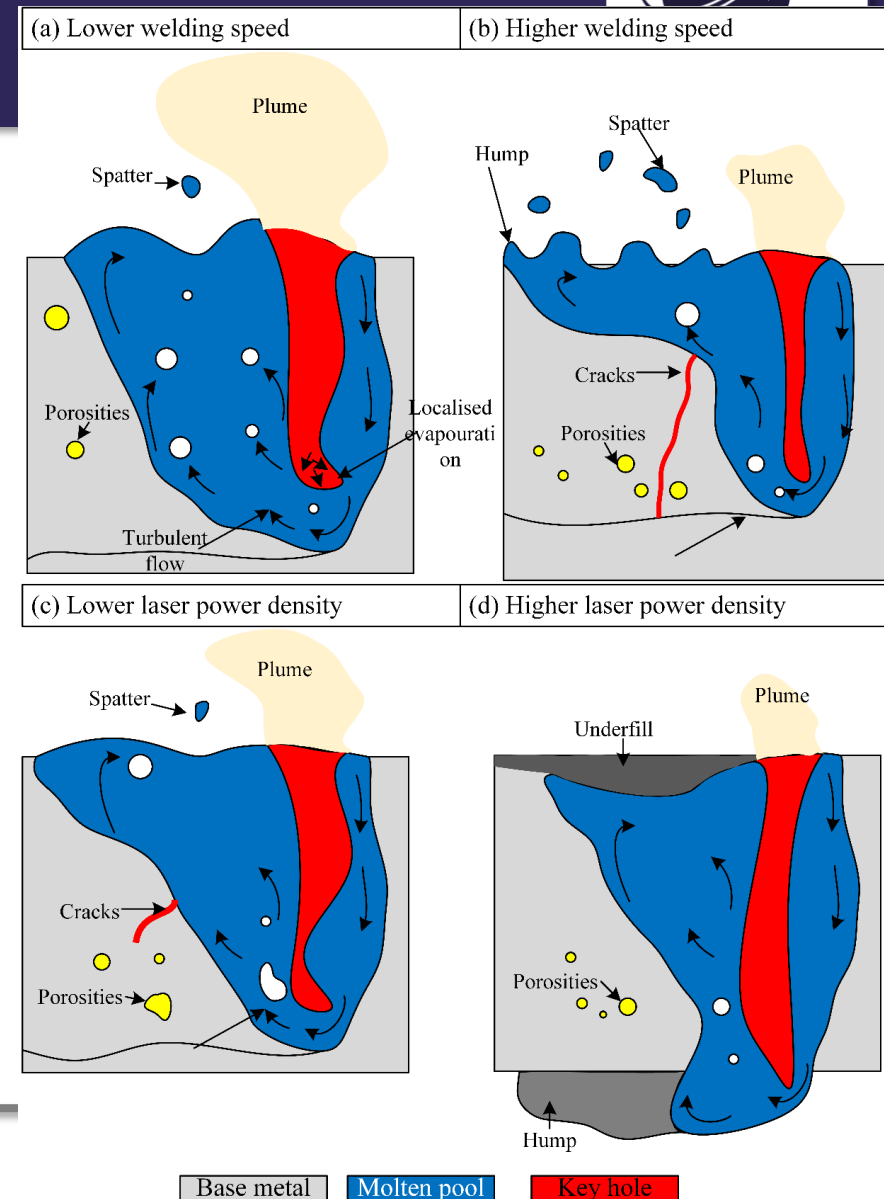


Optical micrograph of the longitudinal cross-section of the weld showing pores trapped in the fusion zone with respect to the penetration depth

Defect formation during laser welding

Internal or Invisible defects

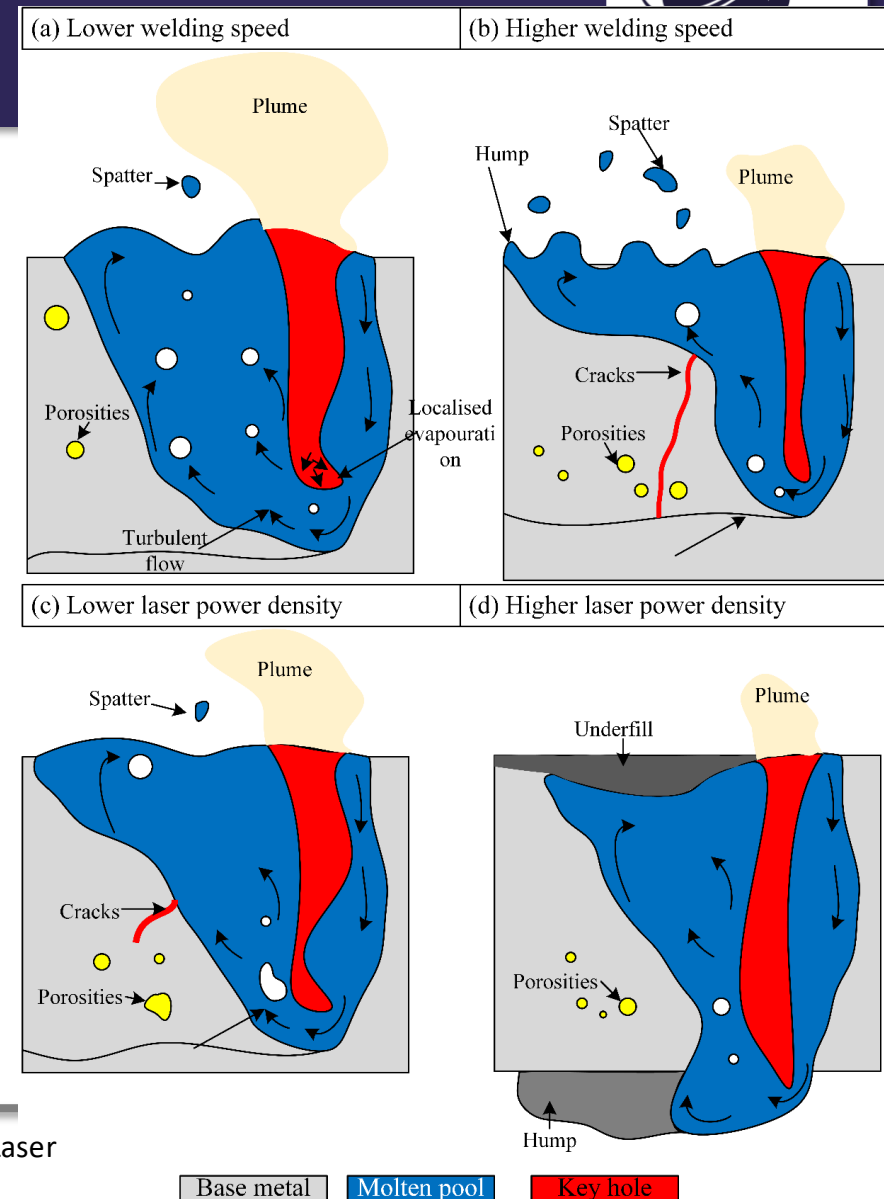
- In laser welding, particularly when employing high power laser beams, the formation of **porosity** is a prevalent defect observed in deeply penetrated weld.
- **Porosities** along with other defects such as **solidification cracking** and **liquation cracking**, primarily occurs in the fusion zone and heat-affected zones (HAZ) of aluminium alloys .
- These internal defects, often invisible to the naked eye, can significantly degrade mechanical properties and even lead to catastrophic failures, making their detection during the welding process particularly challenging.
- The formation of porosities is linked to the interaction of multiple phenomena during welding such as gas entrapment and instability within the keyhole in the fusion zone as it cools and solidifies.



Defect formation during laser welding

Internal or Invisible defects

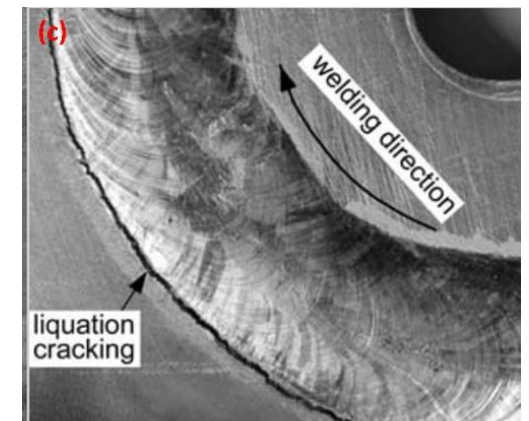
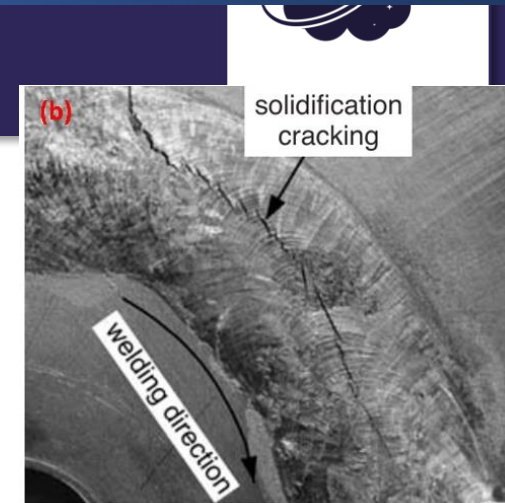
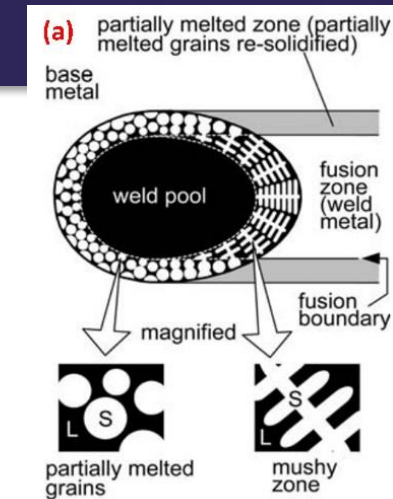
- Porosity significantly weakens the joint strength and reduces the structural integrity of the welded component.
- The primary cause of gas-induced porosity includes inadequate shielding gas coverage and contamination of the base metal, which permits atmospheric gases like nitrogen and hydrogen to infiltrate the molten pool, forming pockets of porosity defects.
- The gas-induced porosities typically manifest in the form of spherical pores with relatively smaller size ($\sim < 100\mu\text{m}$) within the fusion zone.
- Moreover, the keyhole induced porosities are formed during welding attributed to the unstable phenomenon from the vapour keyhole and the surrounding molten pool subjected to a continuous closing and opening.
- The high vapour pressure from the plumes intermittently causes the keyhole to close, forming uneven shaped porosity defect, before re-opening and enlarging to origin size again. Many studies have reported that, establishing a steady keyhole shape leads to reduced probability of porosity formation.



Defect formation during laser welding

Cracking

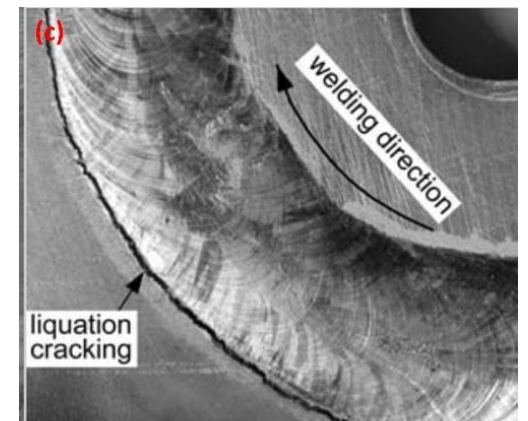
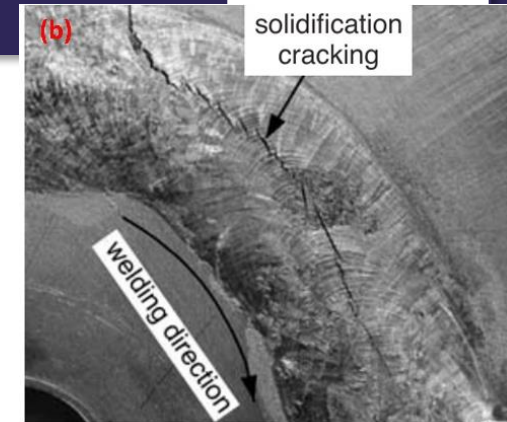
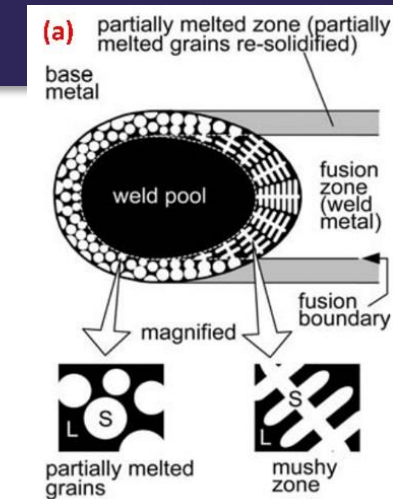
- Cracking within the weld fusion zone is categorised into two types based on the area of occurrence in the weld.
- Solidification cracking occurs in the semi-solid zone of the fusion region during the terminal stages of weld metal solidification.
- Conversely, liquation cracking, manifests in the partially melted zone (PMZ) during the solidification of the liquated material
- Following the molten pool, the material enters a mushy zone consisting of dendrites (S) and the inter-dendritic liquid (L) which then transitions into the fully solidified fusion zone, leading to a potential solidification crack sensitive region.
- The PMZ consisting of partial melted base metal grains (S) and intergranular liquid, is susceptible to liquation cracking.



Defect formation during laser welding

Cracking

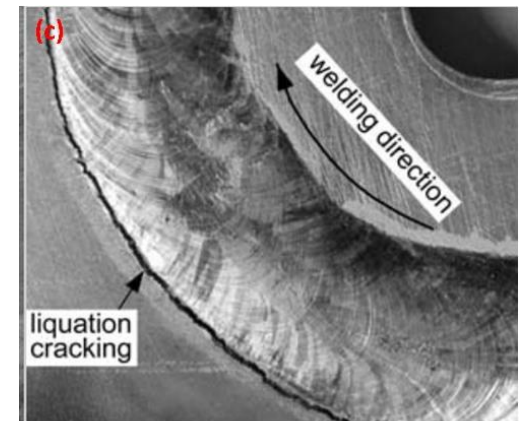
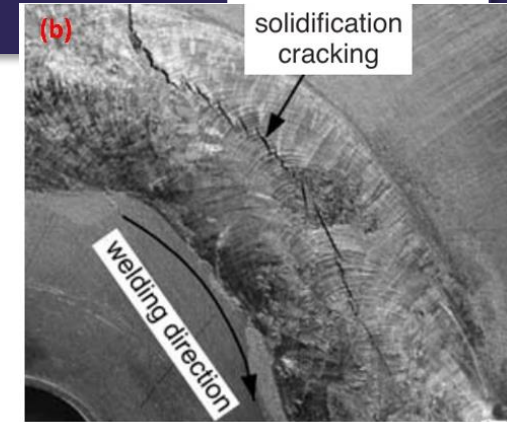
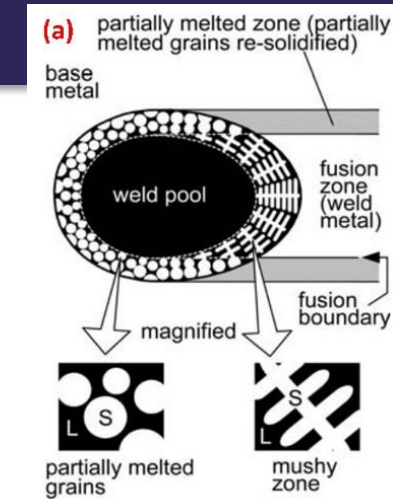
- Liquation cracking in the PMZ occurs due to grain boundary liquation and can propagate if the solidifying and contracting weld metal is stronger than the PMZ.
- The likelihood of liquation cracking increases with the material's propensity to liquate, which is influenced by the freezing temperature range and the fraction of liquid during freezing.
- For instance, aluminium 7xxx and 5xxx series alloys liquates more easily than 6xxx alloys, which have narrower freezing temperature ranges and lower fraction of liquid during freezing.
- Liquation cracking can be reduced by adjusting the weld-metal composition using filler wires and reducing the restraint conditions applied on the fusion zone



Defect formation during laser welding

Cracking

- However, solidification cracking is particularly critical for 6xxx alloys due to their unique composition and susceptibility to higher thermal strains during cooling.
- These alloys typically contain Mg and Si as primary alloying elements, are prone to forming a wide range of solidification temperatures, which leads to solidification cracking.
- The tendency for this type of cracking is aggravated in 6xxx alloys owing to their thermal and mechanical properties often lead to uneven cooling rates and residual stresses, further increasing the risk of crack formation during solidification process.



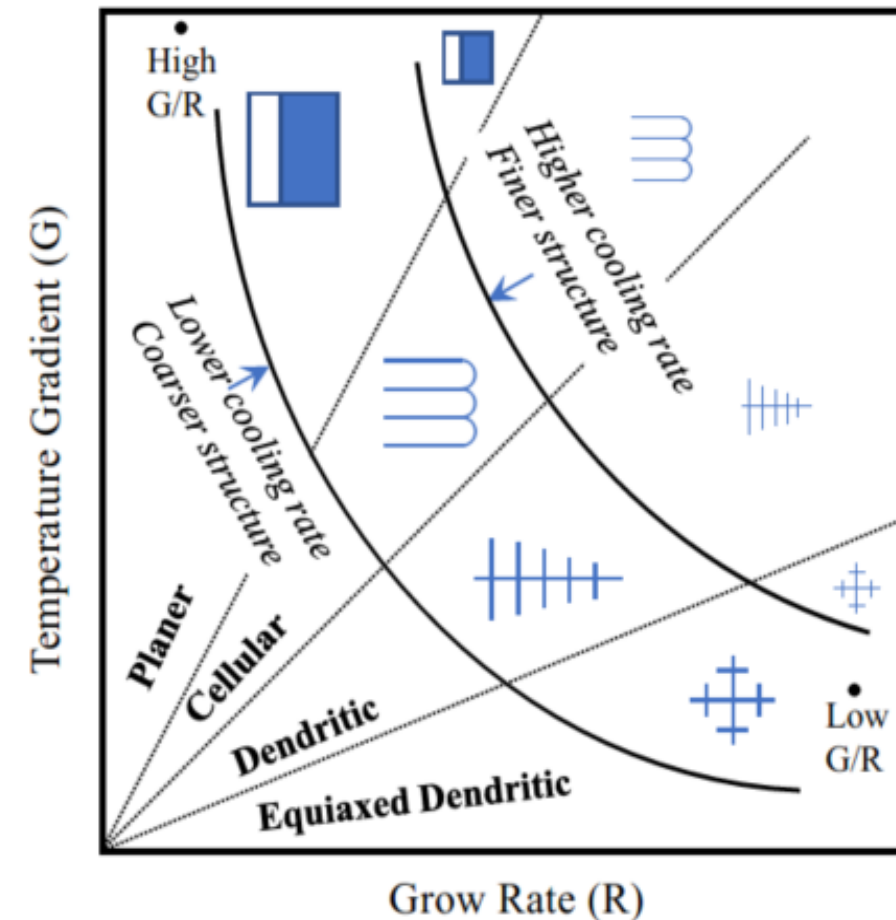
Defect formation during laser welding



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Mechanism of Solidification Cracking: Effect of grain morphology

- The grain structure and size have a significant effect on solidification cracking susceptibility of alloys.
- During laser welding, owing to the faster cooling rates and the solidifying molten pool surrounded by the solid base metal being joined, which can result in epitaxial growth in the fusion zone.
- During solidification, the grains grow perpendicular to the direction of the maximum thermal gradient
- The critical parameters affecting the solidification process are thermal gradient (G), and solidification rate (R), which determines the morphology of the grains formed from the planar, cellular, columnar and equiaxed grains.
- This schematic depicts the size of the solidified structure is defined by the product of G and R termed as cooling rate. The solidified grain morphology is a ratio of G and R . Typically, the columnar and equiaxed grain structure is observed, owing to the high cooling rates during laser welding.



Defect formation during laser welding



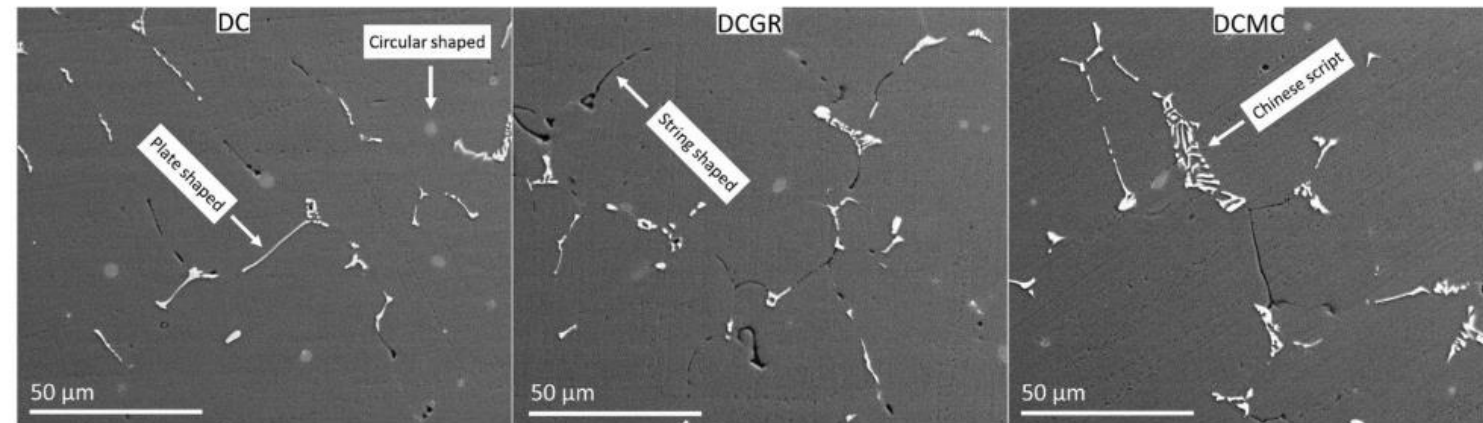
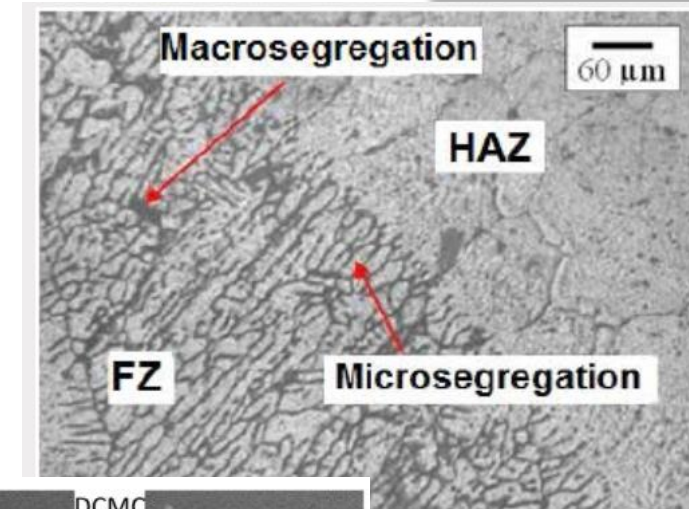
Mechanism of Solidification Cracking: Effect of grain morphology

- Compared with columnar grains, fine equiaxed grains offer good coordination among the deformation of grains, facilitating better accommodation of the shrinkage strains resulting from welding.
- Furthermore, the presence of fine equiaxed grains enhances the effectiveness of backfilling, where a free-flowing liquid film without any restricted movement around the equiaxed grains can fill cavities generated in the fusion zone rather than the columnar structure.
- A large number of grain boundaries in fine equiaxed grain structure serve to minimise the segregation of low melting point eutectics, thereby reducing the crack sensitivity.
- Additionally, the fine equiaxed grains help to distribute the thermal contraction and shrinkage strains across greater number of boundaries, effectively diminishing strains associated with individual grain and lowering the crack sensitivity

Defect formation during laser welding

Mechanism of Solidification Cracking: Micro-segregation

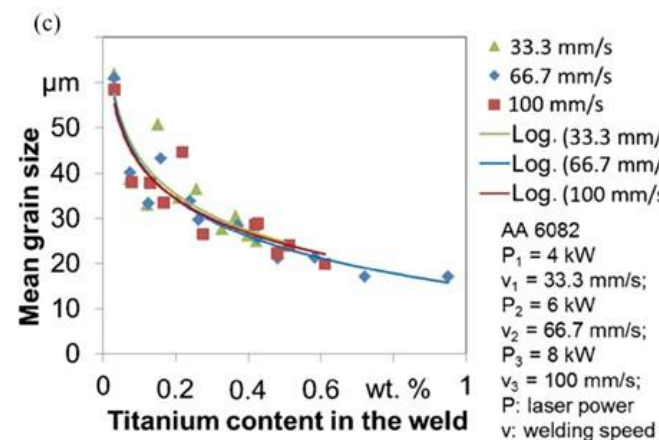
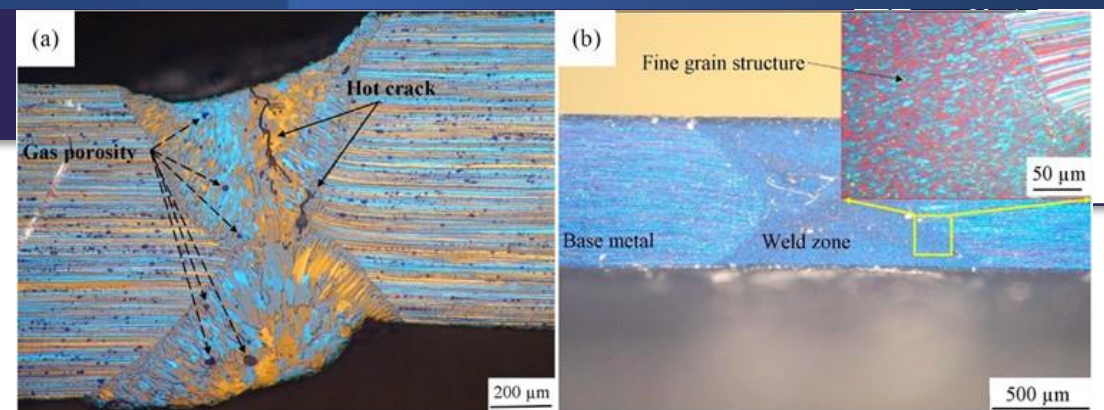
- Solute redistribution during the solidification of molten pool significantly influences micro segregation and solidification cracking.
- However, the transverse tensile stresses that arise from the solidification shrinkage and thermal contraction separate the grains apart.
- By carefully, managing impurities to mitigate the micro-segregation of eutectic Mg_2Si compounds and narrowing the solidification temperature range, the risk of solidification cracking can be significantly reduced.



Defect formation during laser welding

Mitigation of Solidification Cracking: Grain refinement

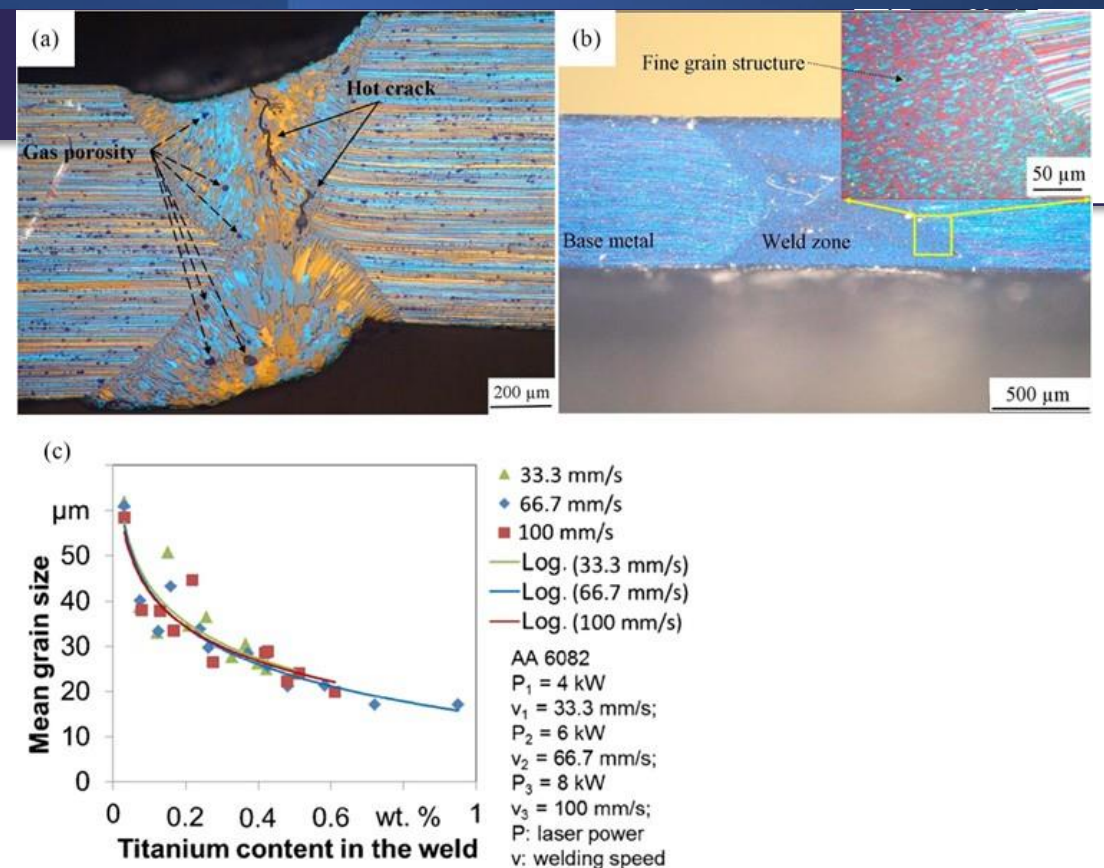
- Building upon the understanding of strain related and the metallurgical factors influencing solidification cracking, one effective strategy to mitigate this is through refinement of the grain structure during solidification.
- It helps to distribute the thermal strains more evenly and reduces the segregation near the grain boundaries in the mushy zone that typically occurs during welding.
- Significant grain refinement in the fusion zone is achievable by inducing the nucleation of grains during solidification.
- It helps to change the coarse and columnar grains, which are the reasons for lower resistance to strains and solidification cracks, to equiaxed and finer sizes.



Defect formation during laser welding

Mitigation of Solidification Cracking: Grain refinement

- Increasing the number of grain boundaries across the width of the weld leads to a reduction in crack susceptibility and further adding some alloying additives helps to control segregation of eutectics and cracks during welding.
- For instance, TiborTM, which contains titanium (Ti) and boron (B) as the grain refiner, is added to the molten pool during laser welding of Al-Mg4.7-0.21Si and 5083 aluminium alloy as depicted in Figure.
- Although the cooling rate is high during laser welding, this refiner had a significant role in reducing the grain size. It is reported that to achieve more equiaxed and finer grains in high-speed welding, more TiborTM is required.

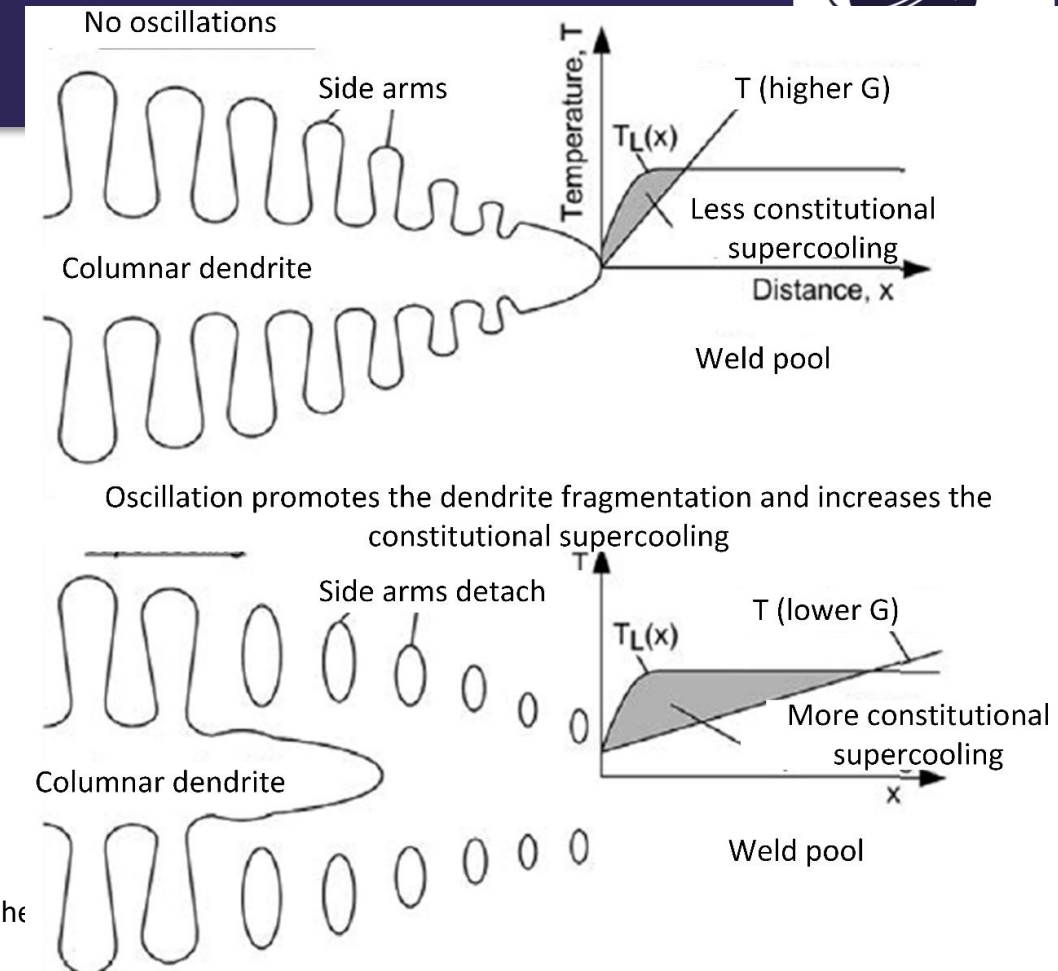


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- Z. Tang, F. Vollertsen, Influence of grain refinement on hot cracking in laser welding of aluminum, Welding in the World 58 (2014) 355–366. <https://doi.org/10.1007/s40194-014-0121-3>

Defect formation during laser welding

Mitigation of Solidification Cracking: Beam oscillation

- Beam oscillations has recently emerged as an effective approach, where the laser beam is directed to oscillate in various patterns and directions.
- This technique can refine the grain structure, leading to finer equiaxed grains without the addition of an external material or alloy homogenising the laser welding process.
- Oscillating the laser beam disperses power across the entire fusion zone, creating turbulent molten pool. Oscillatory beam motion during laser welding generates turbulent flow, reducing the stress concentration and facilitates appropriate solute migration.

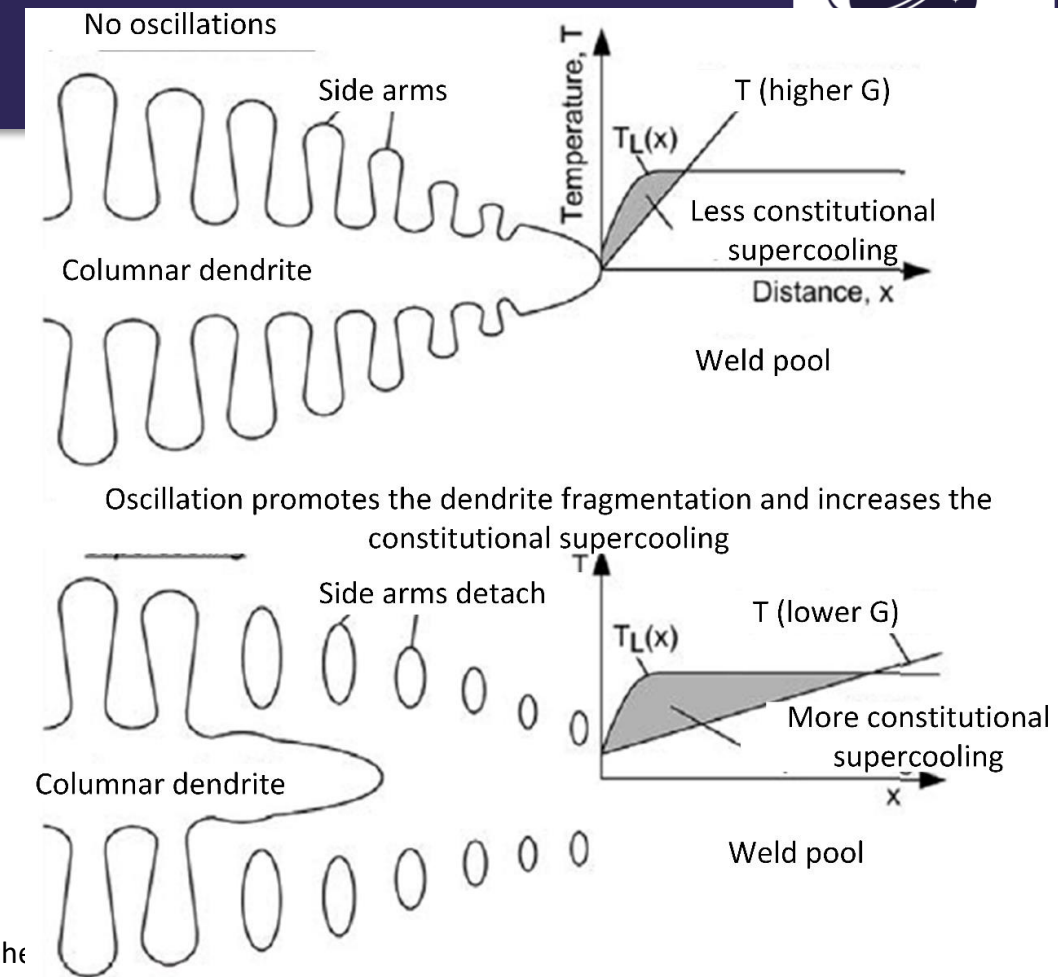


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2. M. Kang, H.N. Han, C. Kim, Microstructure and solidification crack susceptibility of Al 6014 molten alloy subjected to a spatially oscillated laser beam, Materials 11 (2018). <https://doi.org/10.3390/MA11040648>
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4. L. Wang, M. Gao, C. Zhang, X. Zeng, Effect of beam oscillating pattern on weld characterization of laser welding of AA6061-T6 aluminum alloy, Mater Des 108 (2016) 707–717. <https://doi.org/10.1016/j.matdes.2016.07.053>.

Defect formation during laser welding

Mitigation of Solidification Cracking: Beam oscillation

- Laser oscillation expands the molten pool zone and, by extending the laser beam interaction region, can significantly lower the average energy density of the beam.
- This reduction restricts the growth of cellular grains and dendrites that grow along the centreline of the fusion zone. A wider molten pool allows for complete solute diffusion at higher temperatures and extends the solidification time.
- The oscillating laser's dynamic force can break dendrites and aid solute movement as depicted in Figure, owing to the increased constitutional supercooling (it is a condition during solidification where liquidous temperature drops below its normal freezing point without solidifying and leads to dendritic grain structures such as equiaxed) and substantially reduces the cracking susceptibility.

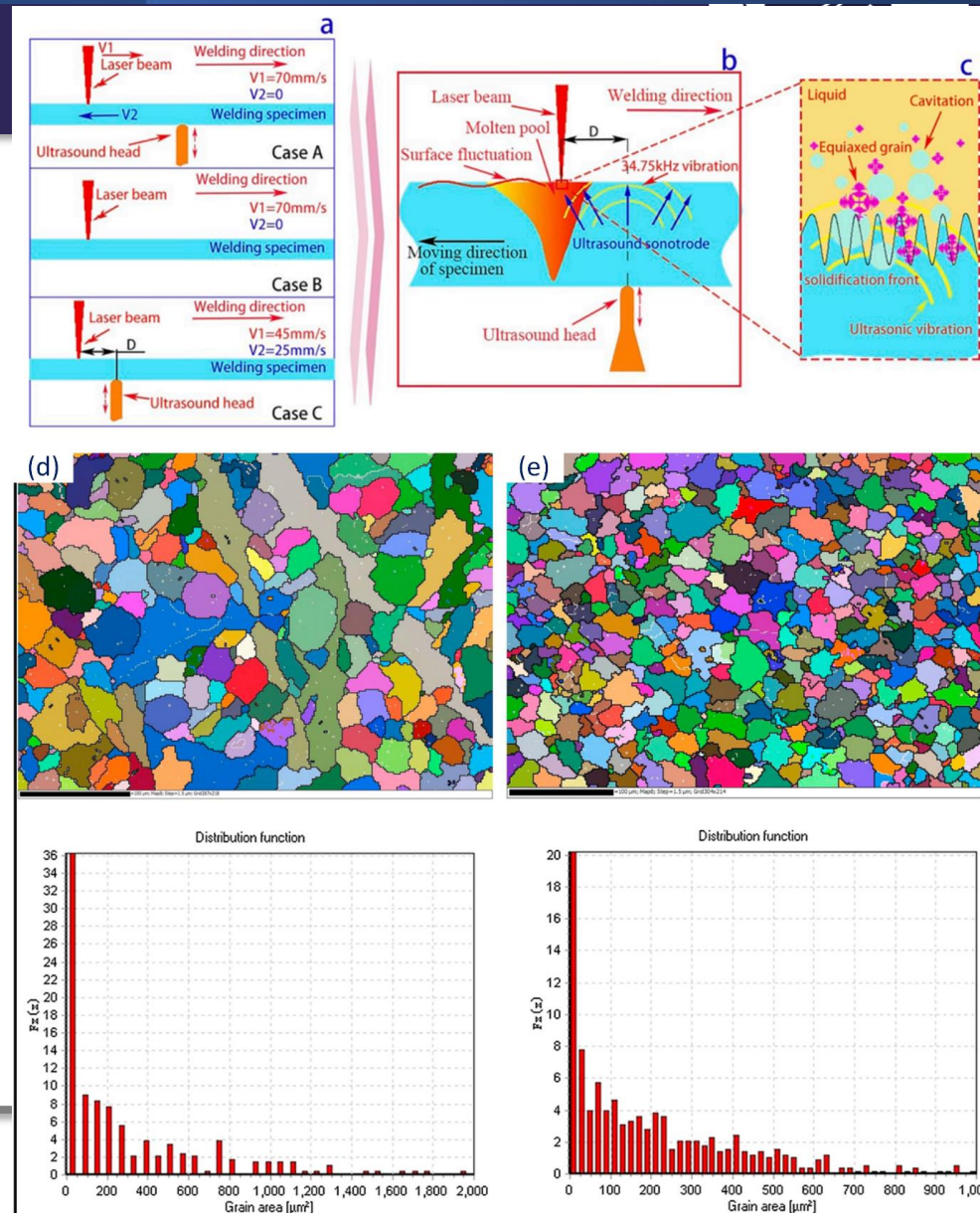


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2. M. Kang, H.N. Han, C. Kim, Microstructure and solidification crack susceptibility of Al 6014 molten alloy subjected to a spatially oscillated laser beam, Materials 11 (2018). <https://doi.org/10.3390/MA11040648>
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Defect formation during laser welding

Mitigation of Solidification Cracking: Inducing Vibration during Welding

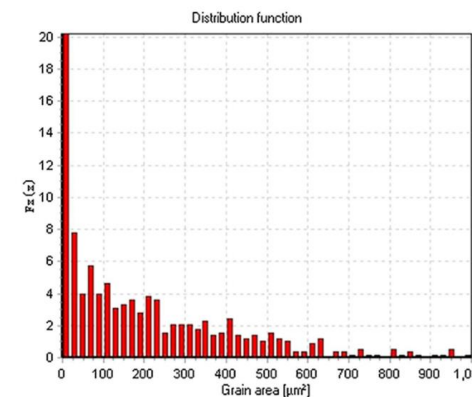
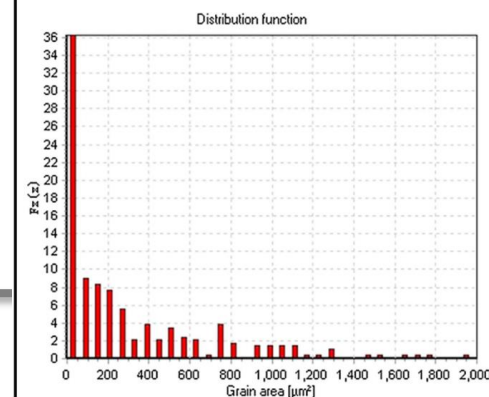
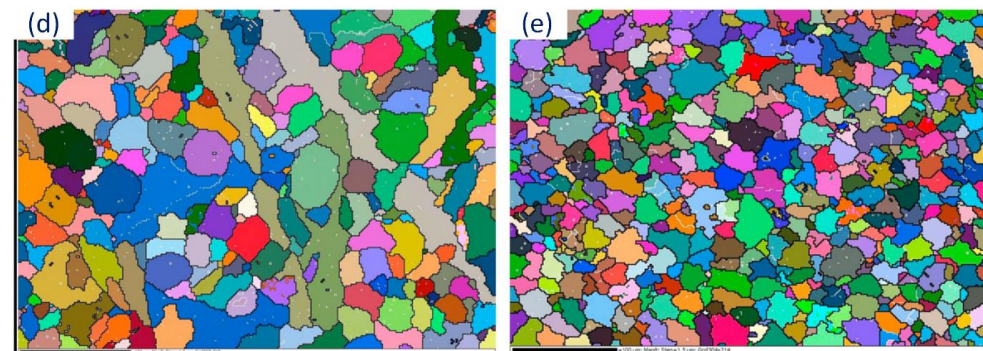
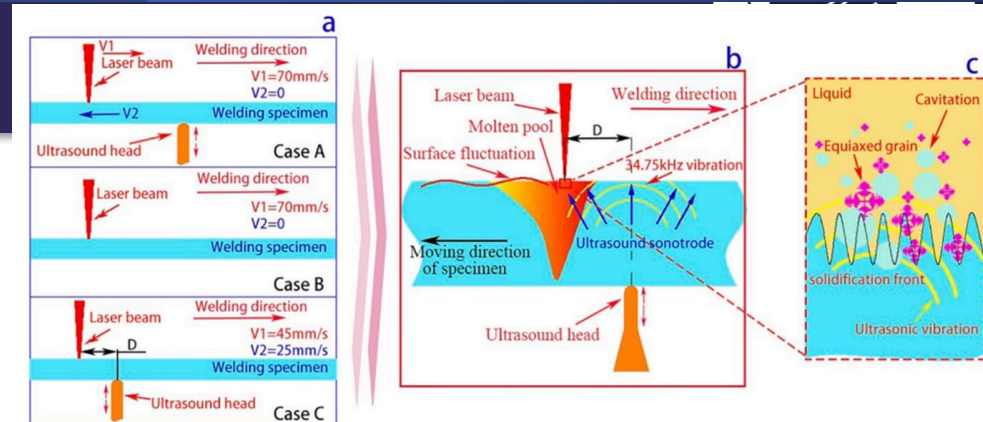
- Vibration techniques, such as ultrasonic vibration and electromagnetic stirring, offer alternative methods to achieve grain refinement and mitigate solidification cracking during the welding process.
 - For example, the use of electrodynamic stirrer during laser welding has been shown to reduce crack sensitivity effectively.
 - This technique promotes a transition from columnar to equiaxed grain structure in aluminium alloys, enhancing the overall quality of the weld.
- Z. Liu, X. Jin, J. Zhang, Z. Hao, J. Li, Microstructure evolution and mechanical properties of SUS301L stainless steel sheet welded joint in ultrasonic vibration assisted laser welding, Opt Laser Technol 153 (2022) 108193. <https://doi.org/https://doi.org/10.1016/j.optlastec.2022.108193>.
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Defect formation during laser welding

Mitigation of Solidification Cracking: Inducing Vibration during Welding

- Ultrasonic vibration during welding claims numerous benefits, including improved material mixing, increased turbulence, enhanced heat generation, and more uniform grain growth, which collectively improve mechanical properties.
- studies have shown the ultrasonic vibration to stabilise the molten pool, and suppressed the circumferential and longitudinal cracking during laser welding of Al-Mg and IN718 alloys.

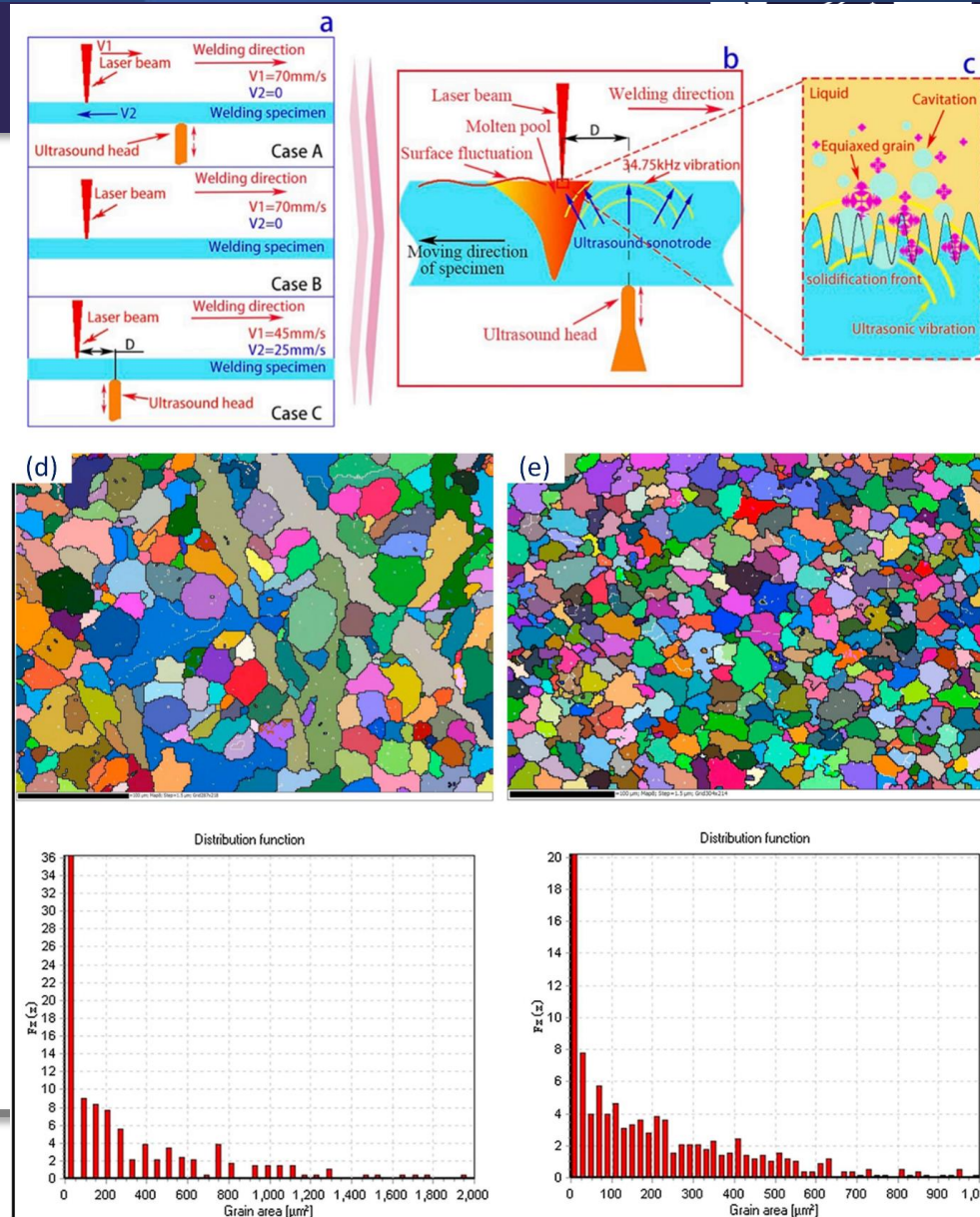


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Defect formation during laser welding

Mitigation of Solidification Cracking: Inducing Vibration during Welding

- Ultrasonic vibration raises the local melting point and, through the explosion of cavitation bubbles.
 - Furthermore, acoustic flows enhance thermal convection, promoting thermal mixing and reducing the temperature gradient within the molten pool.
 - This results in a more homogenous molten pool, decreased porosity and refined grain structures during the crystallisation phase, ultimately improving the mechanical properties of the welded joints.
1. Z. Liu, X. Jin, J. Zhang, Z. Hao, J. Li, Microstructure evolution and mechanical properties of SUS301L stainless steel sheet welded joint in ultrasonic vibration assisted laser welding, Opt Laser Technol 153 (2022) 108193. <https://doi.org/https://doi.org/10.1016/j.optlastec.2022.108193>.
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Defect formation during laser welding



Mitigation of Solidification Cracking: Beam Shaping

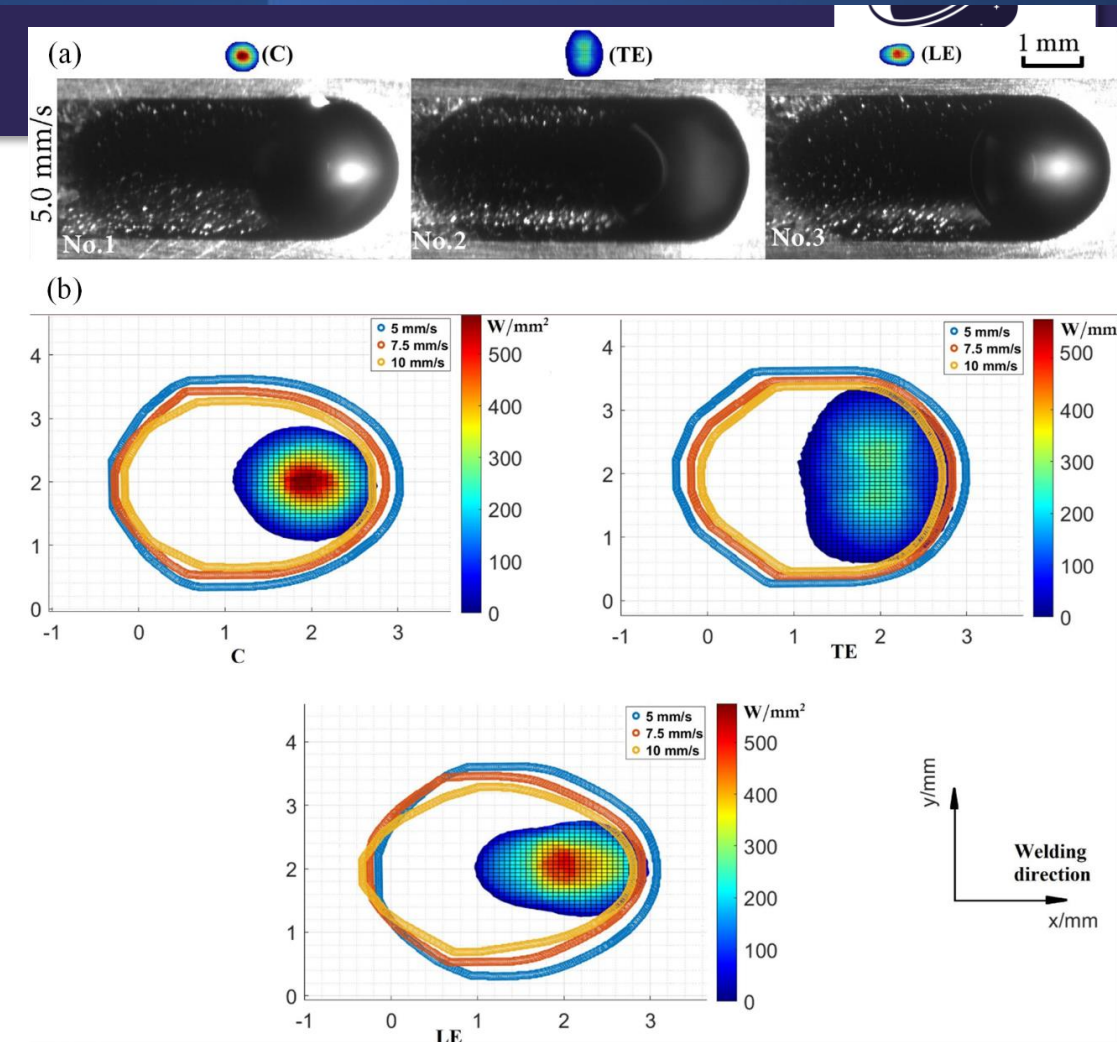
- Beam shaping for higher power, continuous wave, and laser processing is realised by different beam shaping devices utilised. These devices can be mainly categorised into **scanning/deformable mirrors**, **diffractive optical elements (DOE)**, **adaptive optical elements**, Double cladded optical fibre and **Coherent beam combining**.
- **Scanning and deformable mirrors** are instrumental technologies for controlling and maintaining the beam shapes in laser welding, facilitating precise control over the welding process. Galvanometer scanners, a specific type of scanning system, rapidly deflect the laser beam into a designated pattern, allowing dynamic alterations of the beam shape.
- This capability further supports advanced techniques such as “laser beam wobbling” where the beam is oscillated in circular or elliptical patterns to disrupt the molten pool flow and enhance grain refinement within the weld microstructure.

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Defect formation during laser welding

Mitigation of Solidification Cracking: Beam Shaping

- On the other hand, deformable mirrors employ an array of actuators to adjust or deform the mirror surface enabling it to create non-gaussian beams profiles like “top hat” or “doughnut” shapes.
- Customising the beam intensity distribution is essential for controlling the geometry and stability of the molten pool, especially when welding materials which are prone to keyhole stability like aluminium 6xxx alloys.
- As depicted in Figure, the deformable mirrors are used to generate three beam profiles for laser conduction welding such as standard circular beam, transverse elliptical beam, and longitudinal elliptical beam profiles to get a wider and stable molten pool morphology.
- Nonetheless, there are some challenges while utilising the scanning mirror and deformable mirror systems during laser welding. Many studies used a Galvanometric scanning mirror to generate different beam oscillations during welding.

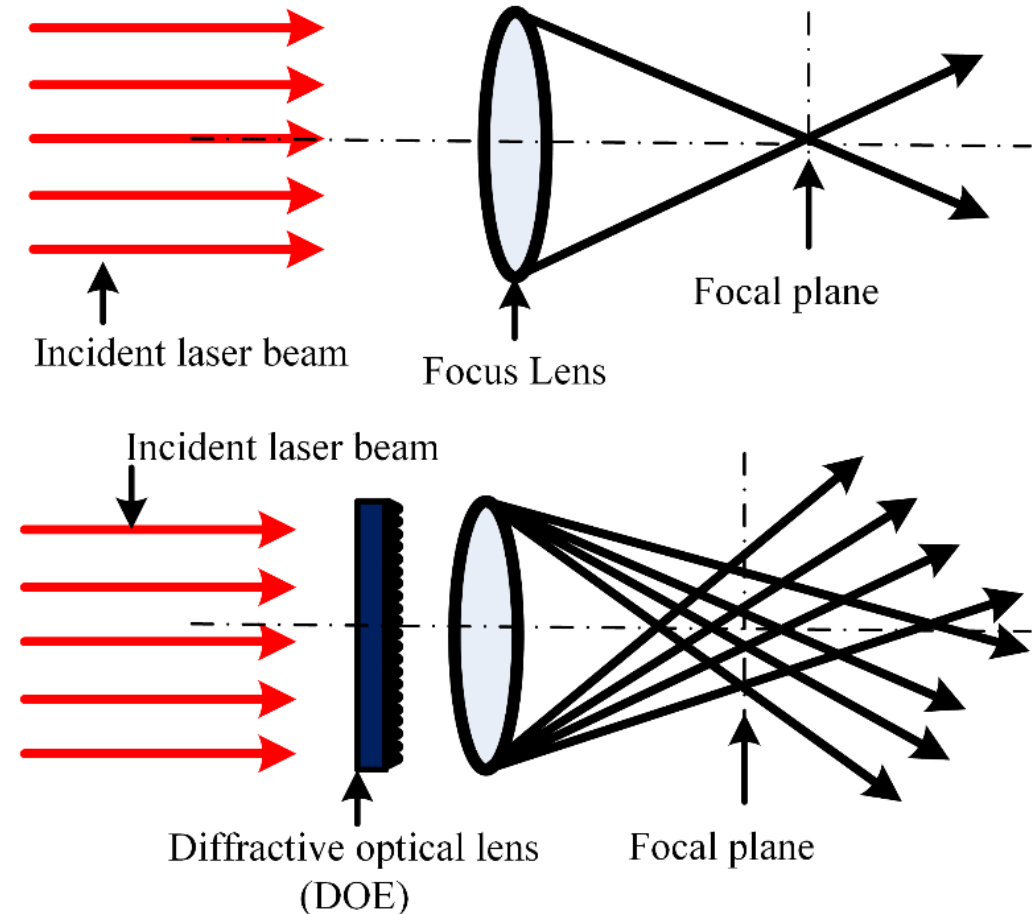


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<https://doi.org/10.1016/j.optlastec.2021.107718><https://doi.org/10.1007/BF02663298>.

Defect formation during laser welding

Mitigation of Solidification Cracking: Beam Shaping

- **Diffractive optical elements (DOEs)** are specialised optical components that employ diffraction patterns to mold laser beam into complex profiles, such as ring-shaped or multi-spot patterns.
- These elements utilise thin microstructure patterns to modify the phase of laser beam that is propagated through them.
- Once custom-designed, these microstructural optical lenses, can precisely manipulate the laser beam to achieve nearly any desired intensity profile or shape.
- DOEs are categorised into two main types based on the beam shapes they generate: beam shaper and beam splitter.

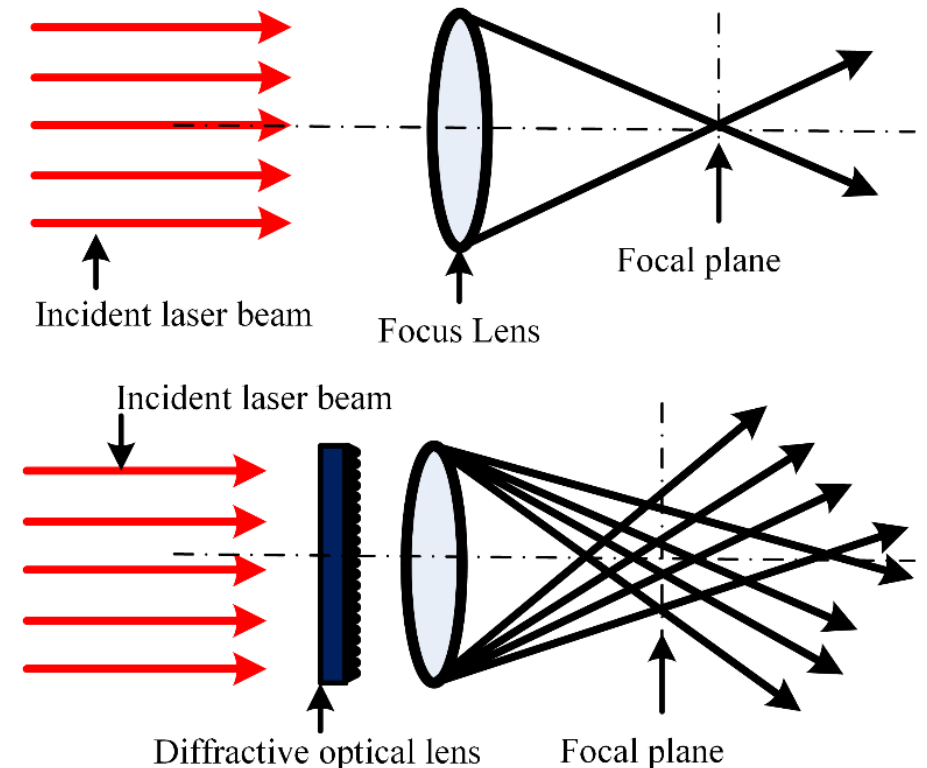


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2. S. Katz, N. Kaplan, I. Grossinger, Using Diffractive Optical Elements: DOEs for beam shaping-fundamentals and applications, Laser Technik Journal 15 (2018) 29–32.
<https://doi.org/10.1002/opph.201870416>.
3. Z. Kuang, J. Li, S. Edwardson, W. Perrie, D. Liu, G. Dearden, Ultrafast laser beam shaping for material processing at imaging plane by geometric masks using a spatial light modulator, Opt Lasers Eng 70 (2015) 1–5.

Defect formation during laser welding

Mitigation of Solidification Cracking: Beam Shaping

- Firstly, diffractive beam shapers are phase optical elements that transform the Gaussian input beam into uniform intensity spots of various shapes such as round, rectangular square, line, or other forms with sharp edges, tailored for specific work planes as depicted in Figure (c).
- Conversely, diffractive beam splitters DOEs divide a single large beam into a several smaller beams, each retaining similar characteristics to the original beam but varying in power and angle of propagation.
- These can form either a 1-dimensional beam array (1xN), 2-dimensional beam matrix or MxN sized array, determined by the diffractive pattern on the optical element surface.



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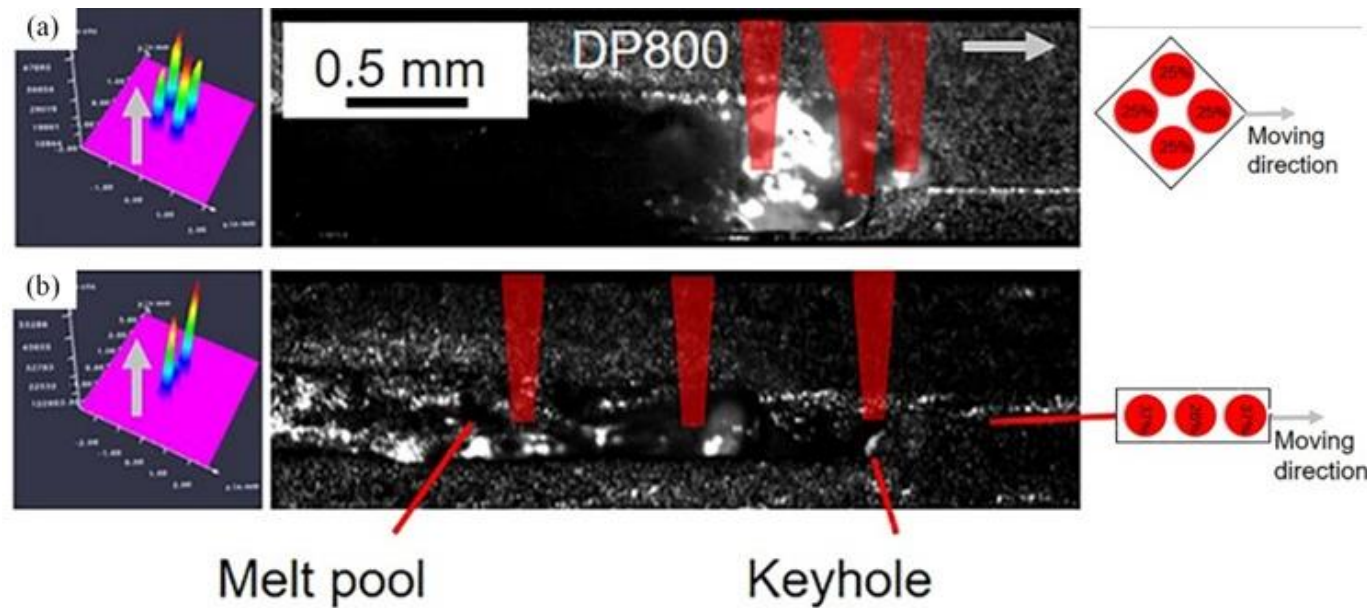
Defect formation during laser welding



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Mitigation of Solidification Cracking: Beam Shaping

- While DOE elements can be custom designed to obtain any required beam shape to modify the grain structure and process quality.
- One key limitation of DOE is that the designed beam profile cannot be altered and is fixed post-manufacture, additionally they have limited depth of focus range, meaning the optimal beam shape is achievable within a narrow defocus range.

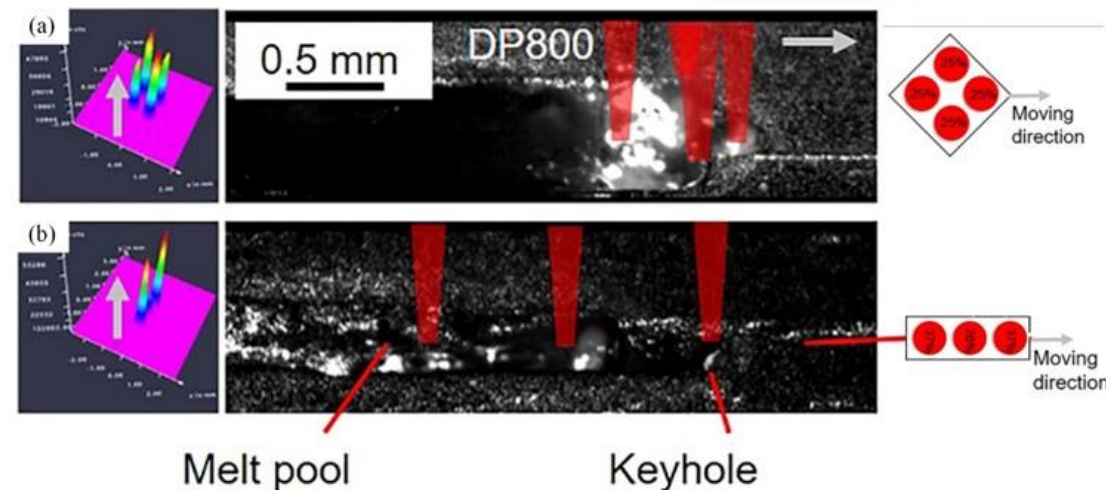


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Defect formation during laser welding

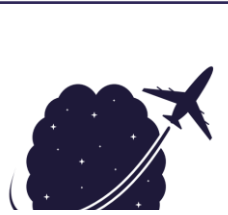
Mitigation of Solidification Cracking: Beam Shaping

- Multi-spot welding, achieved through diffractive beam splitters, has been used to split a single beam and create diverse shapes like a line, and a row of spots for investigating the solidification behaviour.
- One study found that a multi-spot design with two beams in the longitudinal direction of welding increased the penetration depth, while another study used a 2x2 multi-spot grid to improve the keyhole stability during welding as shown in Figure.
- Bessel beam shapes, a broader class of non-diffractive beam shapes have been noted for stabilising melt pool turbulence and extending solidification time, impacting the grain structure during laser additive processing.



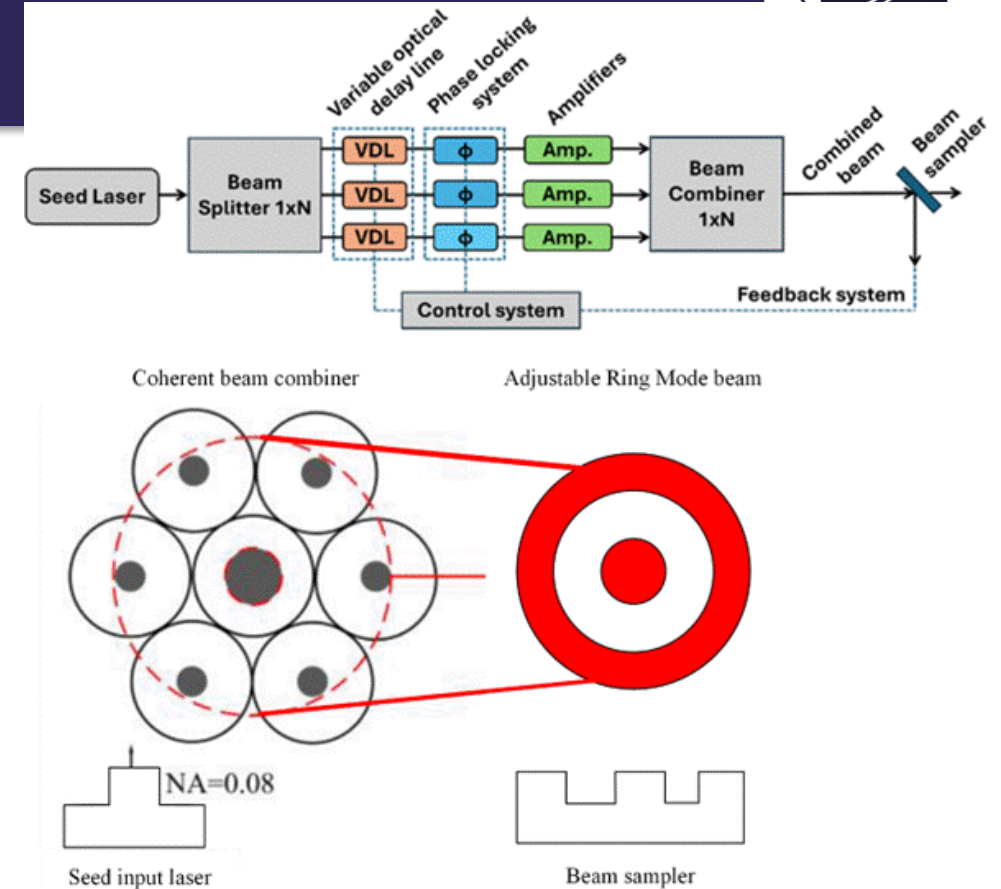
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Defect formation during laser welding



Mitigation of Solidification Cracking: Beam Shaping

- **Coherent beam combining (CBC)** is recognised as an effective technique of power scaling in laser beam technology, by combining multiple laser amplifiers, all seeded by a common laser source, into a single higher-power beam while preserving beam quality and facilitating the formation of any beam shape.
- The adjustable ring mode (ARM) laser beam introduced by Coherent Inc, features a novel dual beam configuration consisting of an inner core and an outer ring-shaped beam which can be independently controlled in terms of power, size and intensity.

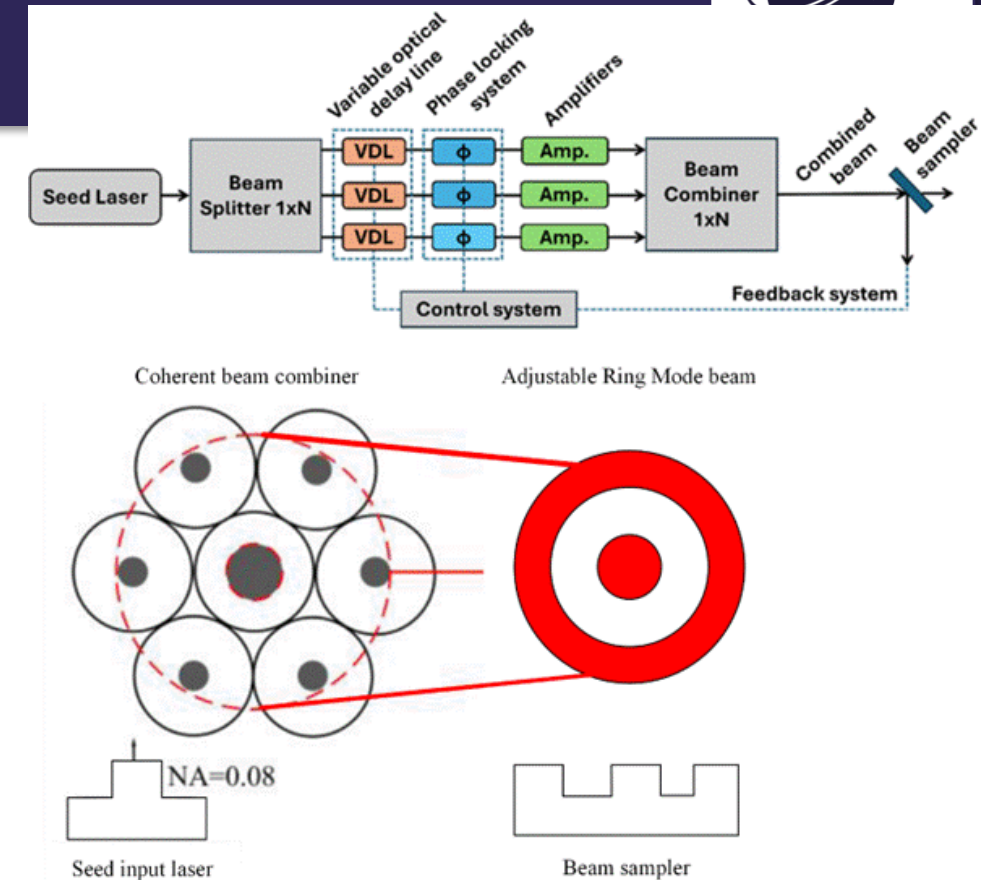


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Defect formation during laser welding

Mitigation of Solidification Cracking: Beam Shaping

- This dual beam configuration is enabled by the ARM laser source's beam combiner which is schematically shown in Figure.
- With this innovative technology, allows for the independent control of power inputs to the outer ring beam and the core beam licensing the generation of varied beam shapes tailored to specific welding applications.
- The change in weld thermal cycle modifies the thermal gradient G , growth rate R , cooling rate $G \times R$ and perturbations in the solidification front G/R .
- Optimising the power ratio favours the grain refinement leading to an increase in strength. Reducing porosity



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Defect formation during laser welding



Type of beam shape	Material	Key findings
Defocussed beam [Axisymmetric]	IN 625	It widens the molten pool and reduces the thermal stresses during solidification. However, defocussing leads to lower penetration and can cause spatters and uneven weld surface.
Twin-spot optics [Axisymmetric]	42CrMoS4	Preliminary study to maintain the temperature gradients and observed a trailing second spot can change the pool geometry and reduces the crack length.
Doughnut-shape [Axisymmetric]	AA 5083	Poor weld quality and cracks at higher welding speeds owing to slower cooling rates using the ring only beam shape.
Core-ring beam (ARM) [Axisymmetric]	AA6005	Optimal selection of core-to-ring power can reduce the formation of cracks by reducing the thermal strains and grain refinement.
Bessel beam shape [Axisymmetric]	SS 316L	Preliminary study during laser additive manufacturing has reported reduced thermal gradients in the depth direction with refined equiaxed grains, nonetheless the propensity to cracking haven't been determined.
Elliptical beam shape [non-axisymmetric]	SS 316L	Refined the grain structure by increasing the thermal gradients and can reduce the crack sensitivity in manufacturing, however, the use of this shape in welding is unexplored.

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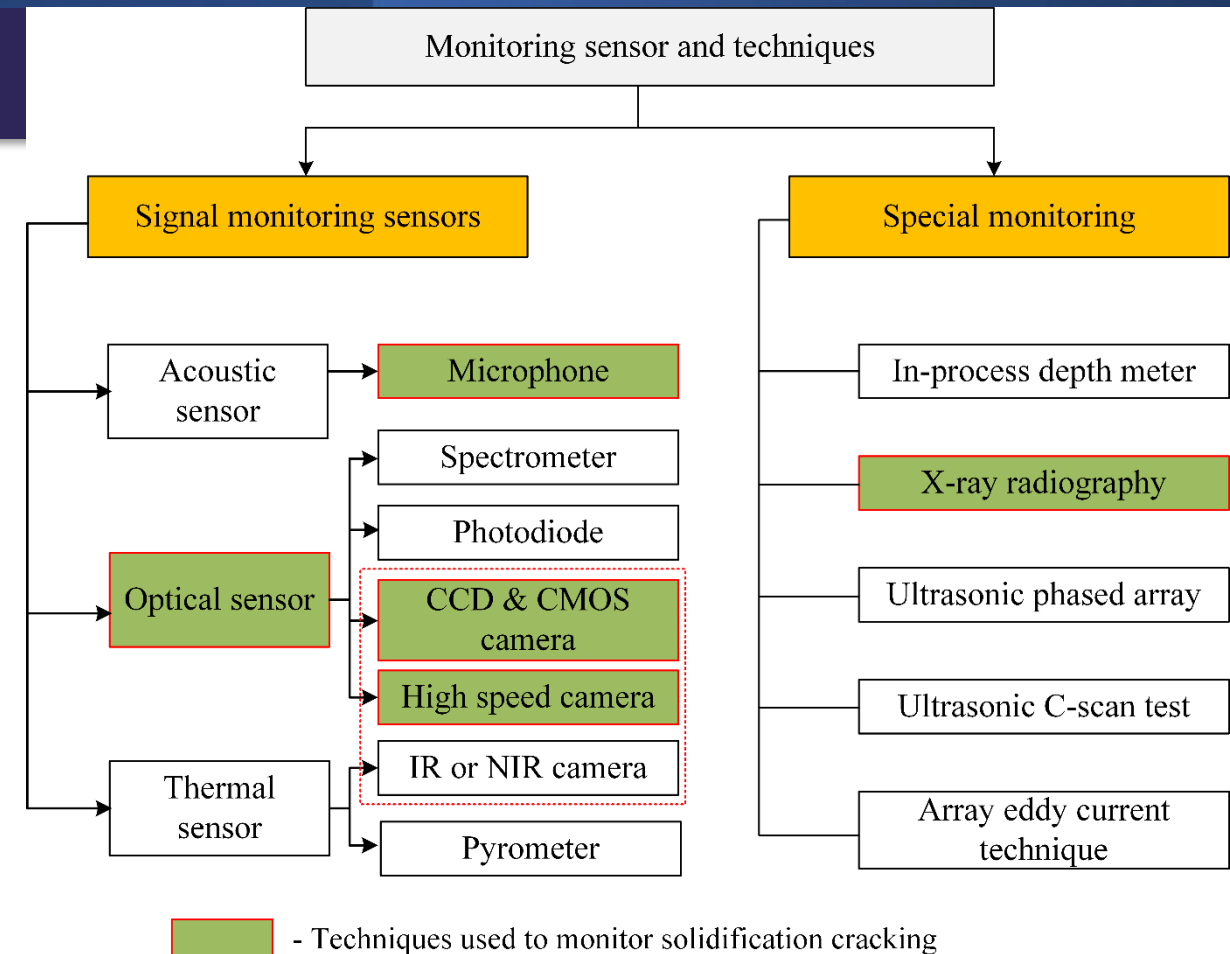
In-situ monitoring of laser welding process



- In-situ monitoring refers to the use of smart manufacturing processes to detect weld quality in real time.
- By combining data from input parameters, process sensor signals and final weld fusion zone characteristics with a system capable of learning and decision-making, the primary goal in automotive applications is the rapid optimisation of weld quality.
- To enhance weld quality control, there is strong interest in developing novel sensors, improving existing technologies, and identifying the best sensor combinations for specific materials and defects. However, the interaction between the laser beam and material is inherently complex, limiting the characterisation of process signatures such as molten pool morphology, and optical radiation, which are crucial for detecting defects such as cracks and molten pool to keyhole instabilities during welding.
- Moreover, the transient nature of the laser welding process with higher plumes, temperatures and rapid solidification makes it difficult to capture the thermal and strain field signatures of cracks.

In-situ monitoring of laser welding process

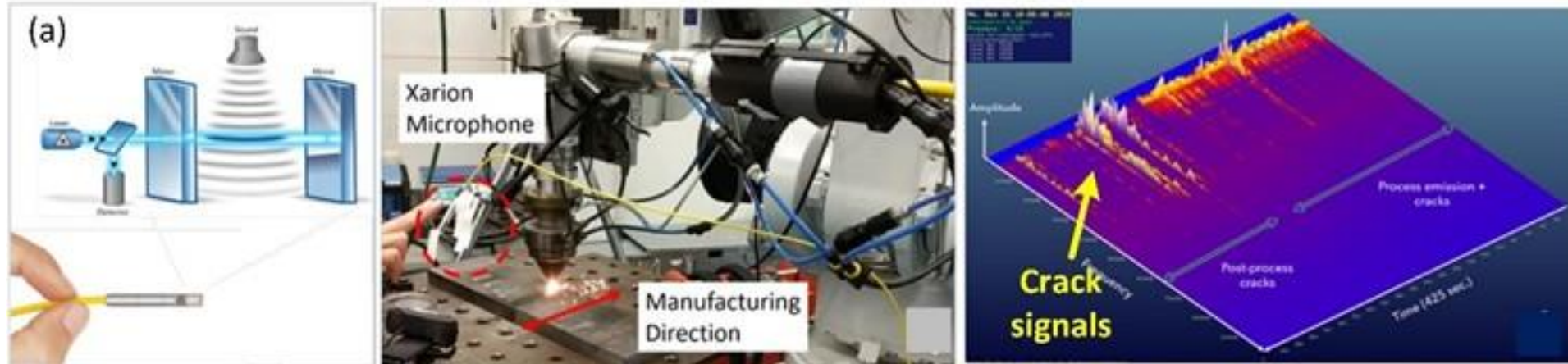
- During laser welding, detection of elements such as **keyhole**, **molten pool**, **plasma** and **spatters** generate various types of welding signals, including **acoustic**, **optical** and the **thermal** signals all of which are intricately linked to welding quality.
- Consequently, implementing a sensor based real-time monitoring is crucial for effectively capturing these welding quality signals within the fusion zone.
- From the acoustic sensor devices, a microphone technology is used that captures broadband airborne acoustic emission of up to 1MHz such as sudden acoustic emission produced by the released energy of cracks.



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In-situ monitoring of laser welding process

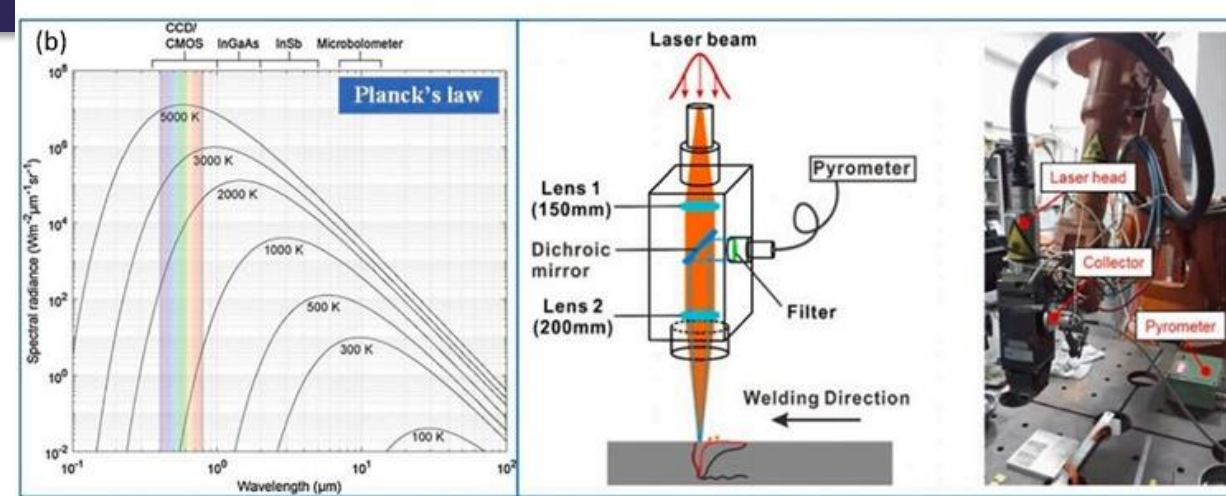
- Using an acoustic sensor technology a process emission of 200 kHz and crack-type signals of 600 kHz difference were detected.
- This technology can also be employed to monitor weld depth penetration by detecting the effects of plumes during the welding process.
- The thermal radiation signal is notably strong in laser welding due to the high temperatures generated. Variations in heat input are likely to result in significant changes in thermal radiation within the fusion zone.
- Current literature cites various detection sensors and systems, including thermocouples, photodiodes, and infrared cameras as potential tools for this.



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In-situ monitoring of laser welding process

- However, these sensors generally fall short within laser welding environment, which demand rapid and precise measurements at temperatures crossing 3000°C and higher rates of solidification during welding process.
- A novel temperature monitoring technique involves the use of pyrometers to monitor thermal radiation during welding.
- Pyrometers operate on the principle of an ideal black body at varying temperatures emit radiation with varying wavelength with sensitivity range following plank's law as shown in Figure, which has the capability of detecting radiance emitted by moving molten pool. Nonetheless, the application of pyrometers is somewhat limited owing to significant drawbacks such as slow response times and substantial interference from the high thermal field and plasma.

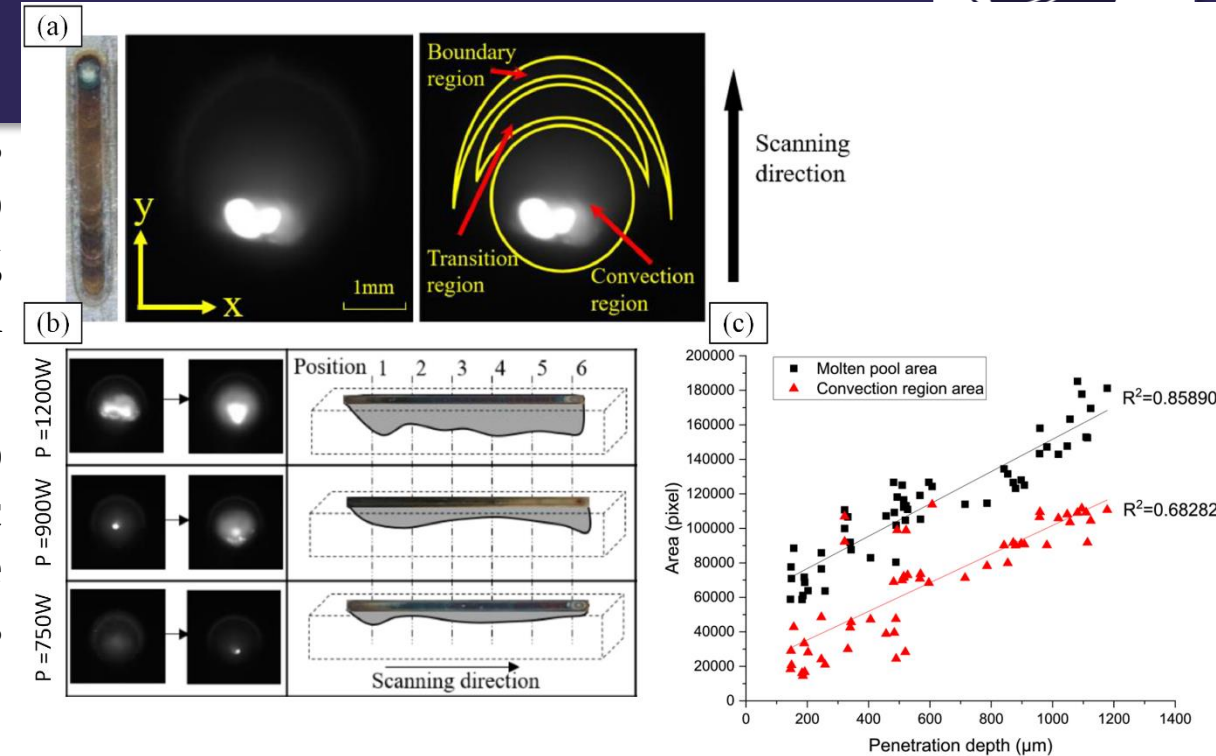


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In-situ monitoring of laser welding process

Camera-based and high-speed imaging techniques

- In recent years, the vision-based monitoring technique has been suggested to be one of the most intuitive methods due to the advantages of higher spatial measurements and yielding more information as compared to the above-mentioned techniques.
- Additionally, high-speed imaging sensors capturing 20000 to 50000 frames per second can aid in monitoring the dynamic behaviours of the molten pool, and plume, enabling accurate location and identification of the welding defects such as cracks and porosity generated from keyhole collapse.
- They consist of CCD (charged coupled device) and CMOS (Complementary metal oxide semiconductor) that detect light and convert it into electrical signals to generate an image during monitoring.

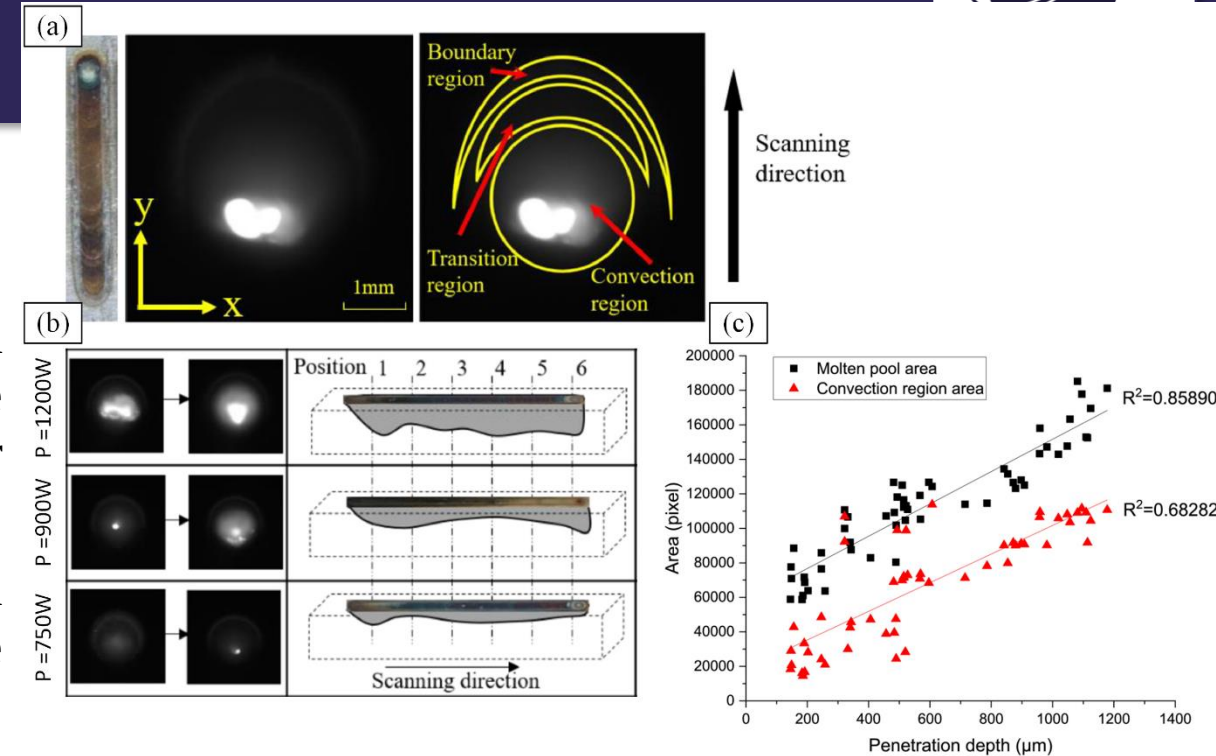


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Camera-based and high-speed imaging techniques

- High-speed imaging is usually generated using CMOS cameras as they can read pixels in the image individually, enabling features like windowing and higher frame rates.
- These camera-based sensors can be used as both co-axial and off-axial configurations and are mainly used to obtain keyhole and molten pool images during traditional/remote laser welding.
- They were further used to identify weld surface width and penetration depth, keyhole area and shadow region of the plumes during welding as key performance indicators.
- Although co-axial monitoring of the molten pool, captures images and detects the irregularities generated from the laser-to-material interaction, off-axial monitoring has the flexibility of observing both the keyhole and molten pool.

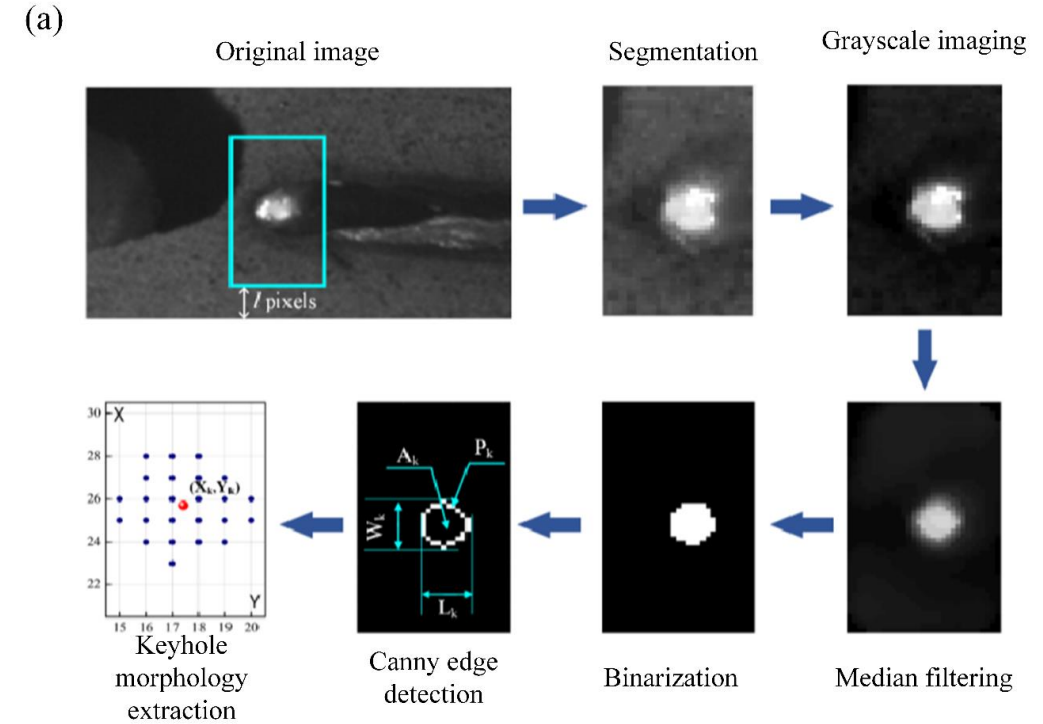


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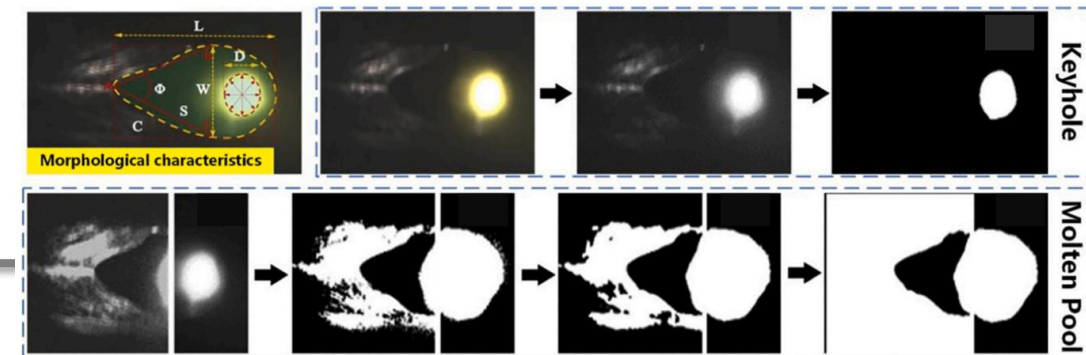
In-situ monitoring of laser welding process

Camera-based and high-speed imaging techniques

- Images of the keyhole captured through the high-speed camera-based monitoring systems, where Gray-scale processing with binarization was utilised to outline the keyhole morphology.
- It aided in observing the frequent keyhole collapsing which significantly affected the penetration depth and porosities observed during welding.
- Additionally, the morphology of the molten pool, including its length, width, and area has been analysed to evaluate its impact on weld quality.
- These features were detected using common image processing techniques such as thresholding and binarizing at different levels to detect both keyhole and molten pool during the welding process.



(b) Thresholding and binarizing high thresholding - keyhole and low thresholding - molten pool

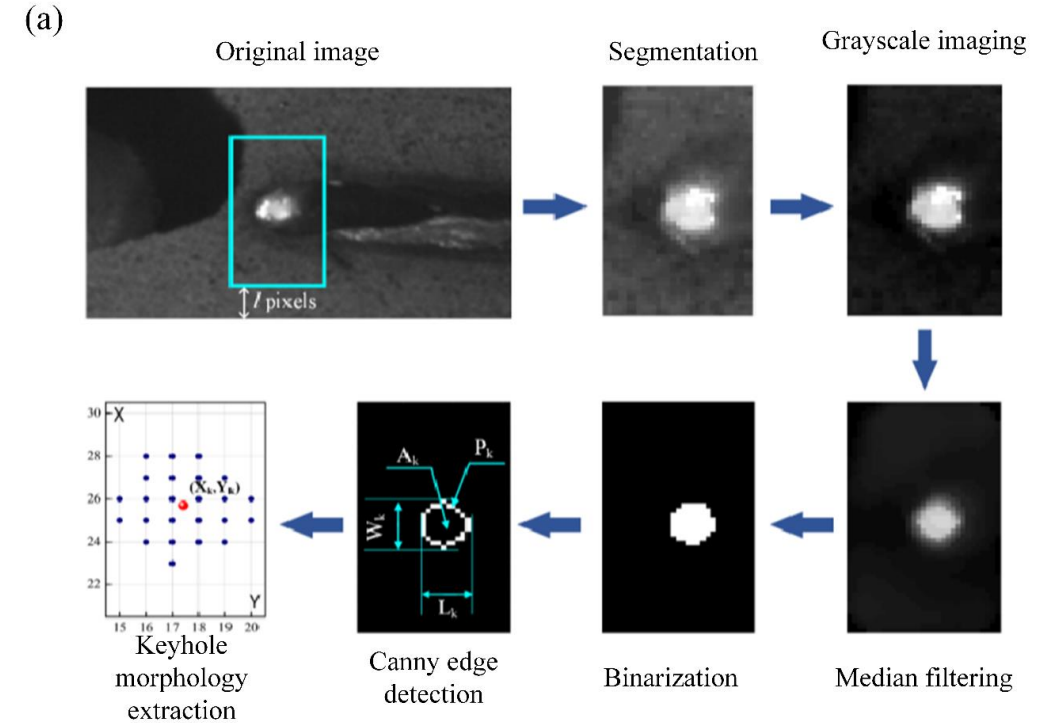


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2. D. Wu, et al., Progress and perspectives of in-situ optical monitoring in laser beam welding: Sensing, characterization and modeling, J Manuf Process 75 (2022) 767–791.

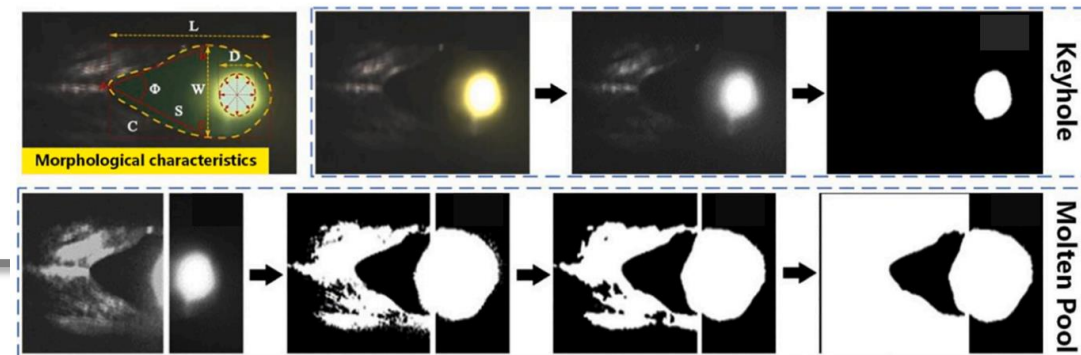
In-situ monitoring of laser welding process

Camera-based and high-speed imaging techniques

- Furthermore, a series of frame subtraction and image morphological operations to predict the top surface molten pool shape and identified its effect on porosity and weld quality from the top surface.
- It should be noted that these methodologies only provide an approximate interpretation of the shape of top molten pool and may misinterpret the true form of the molten region, especially, when considering the dynamic movement of the liquid and the complex texture of the images of fusion zone.
- Furthermore, recent image processing problems focus on using convolutional neural networks (CNN) to detect the molten pool morphology and to classify weld defects.



(b) Thresholding and binarizing high thresholding - keyhole and low thresholding - molten pool

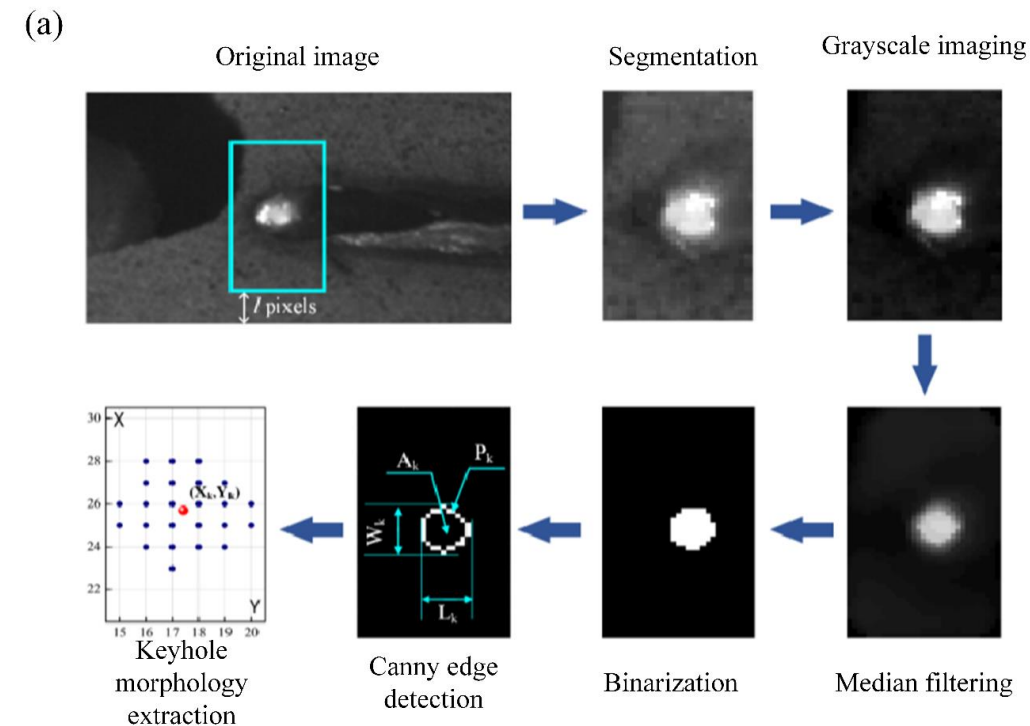


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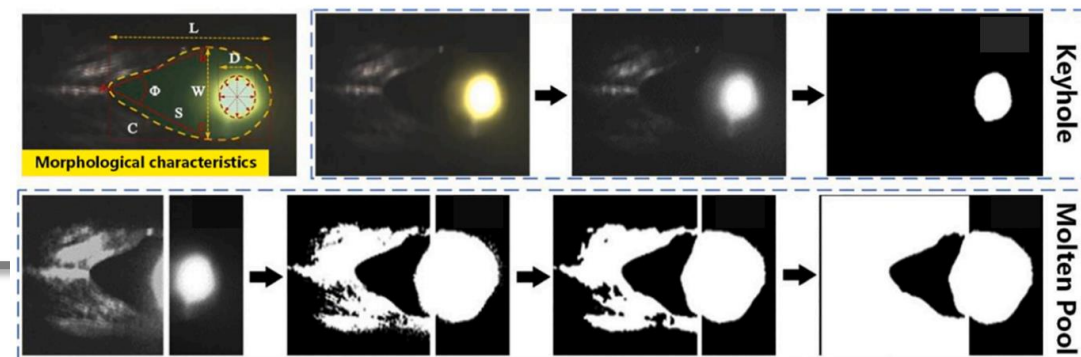
In-situ monitoring of laser welding process

Camera-based and high-speed imaging techniques

- These methods, although potent, require a large diverse set of labelled data which is particularly challenging to produce in this context of welding.
- Therefore, due to these considerations, studies have opted against deploying CNN in welding scenario analysis.
- Nevertheless, there is a crucial need for a robust methodology that utilises image processing techniques to accurately detect the molten pool shape, overcoming challenges posed by spatters and high thermal fields during welding.



(b)
Thresholding and binarizing high thresholding - keyhole and low thresholding - molten pool



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In-situ monitoring of laser welding process

Camera type	Features detected in laser welding	Resolution (pixels) and (frame/ frame per second)	Image processing algorithm
CCD camera	Keyhole detection to detect the penetration depth	644 × 239	Binarization and thresholding
CCD camera	Detecting weld penetration status	648 × 488 (210 frames)	Canny-edge detection
CCD camera	Melt pool morphology measurement	659 × 493 (200 frames)	Principle component analysis with machine learning
High-speed CMOS camera	Recording laser-induced plasma	64 × 64 (7915 fps)	Principle component imagery
High-speed camera (Photon FASTCAM)	Keyhole detection from the top surface (penetration depth)	512 × 384 (50000 fps)	Binarization and morphological
NAC-IR high-speed camera	Molten pool width using thermal radiation	1000 fps	Fourier transform imaging
High-speed CMOS camera	Detecting the molten pool shadow for detecting molten pool morphology	512 × 500 (5000 fps)	Binarization and thresholding along with morphological
Photons A4 high-speed camera	Penetration based on keyhole and plasma	20000 fps	Thresholding and Correlational analysis
High-speed camera (Olympus, i3)	Vapour plume and keyhole detection and stabilising them	1500 fps	Binarization and edge detection

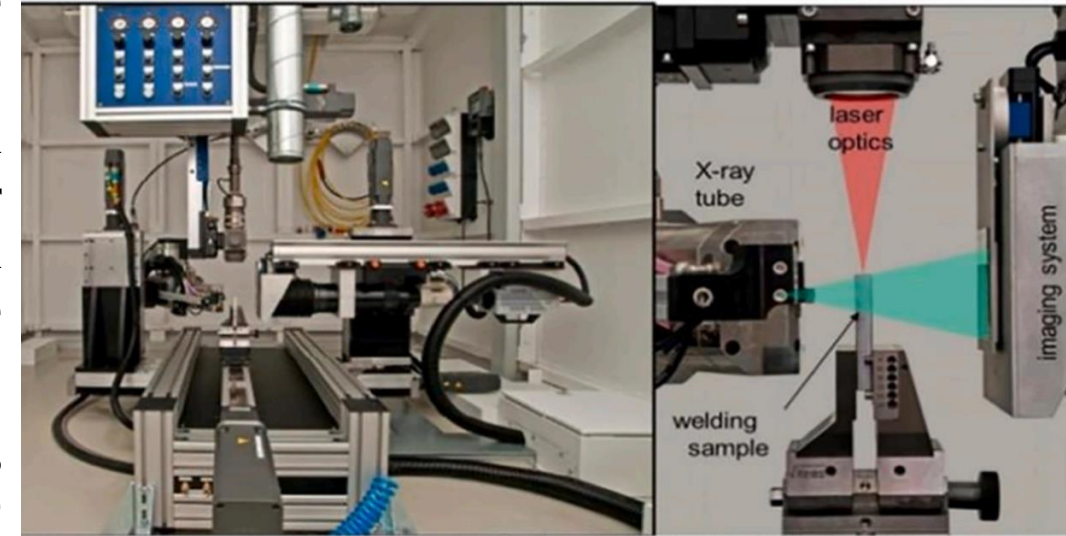
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In-situ monitoring of laser welding process

Special techniques

- Thermal radiation and vision-based techniques primarily monitor the dynamic behaviours of the keyhole, molten pool and vapour plume from a top view.
- However, these methods cannot directly visualise the internal structures of the keyhole and molten pool, which are crucial for determining the final quality of the weld. Additionally, optical sensing techniques provide challenges due to spatters and the intense emissions from plasma provide limited depth information.
- To address these limitations associated with monitoring welding process dynamics, particularly the shape and geometry of the keyhole and molten pool, several novel monitoring methods have recently been developed. They include X-ray imaging, inline coherent imaging, and metal-glass sandwich imaging, which offer a better view of internal weld quality during the welding process.

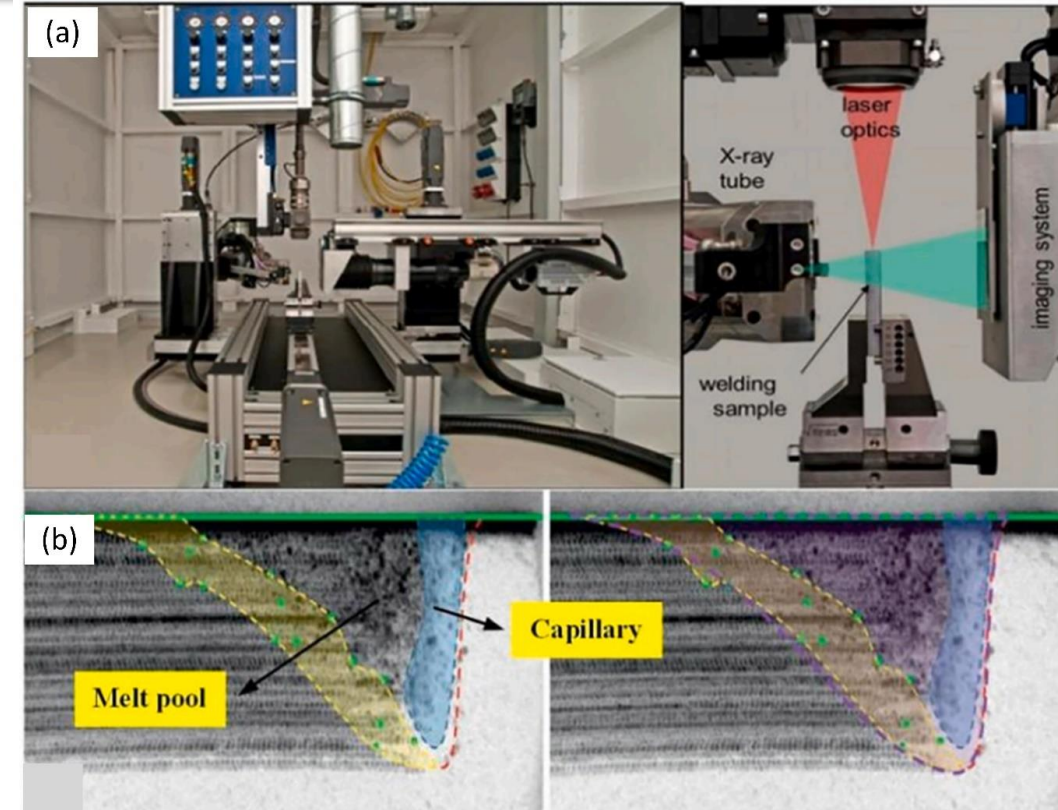


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In-situ monitoring of laser welding process

Special techniques: X-ray imaging

- In-line X-ray imaging is one of the trending methodologies for observing the keyhole capillary with a side view through the material.
- This monitoring helps to reveal the keyhole behaviour, bubble formation, and molten flow inside the fusion zone.
- A clear visualisation of keyhole and molten material can be distinguished owing to the X-ray passing through to the solid and liquid medium at different rates.
- Nonetheless, the X-ray imaging systems are limited to observing thin samples as they struggle to effectively penetrate thicker materials, which are more representative of real-world scenarios.

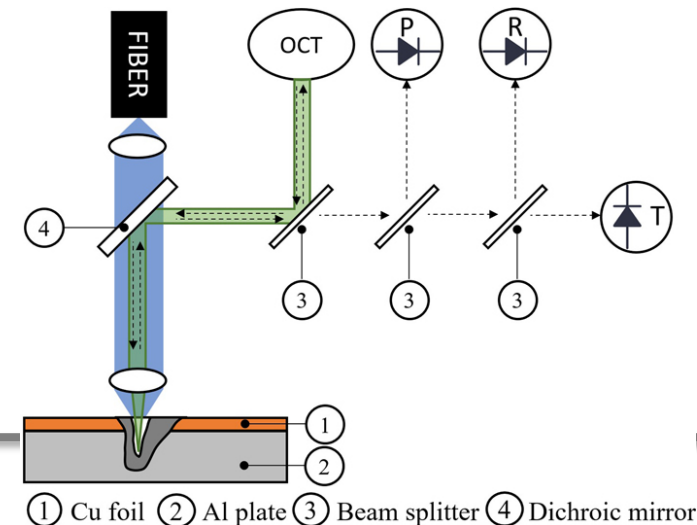
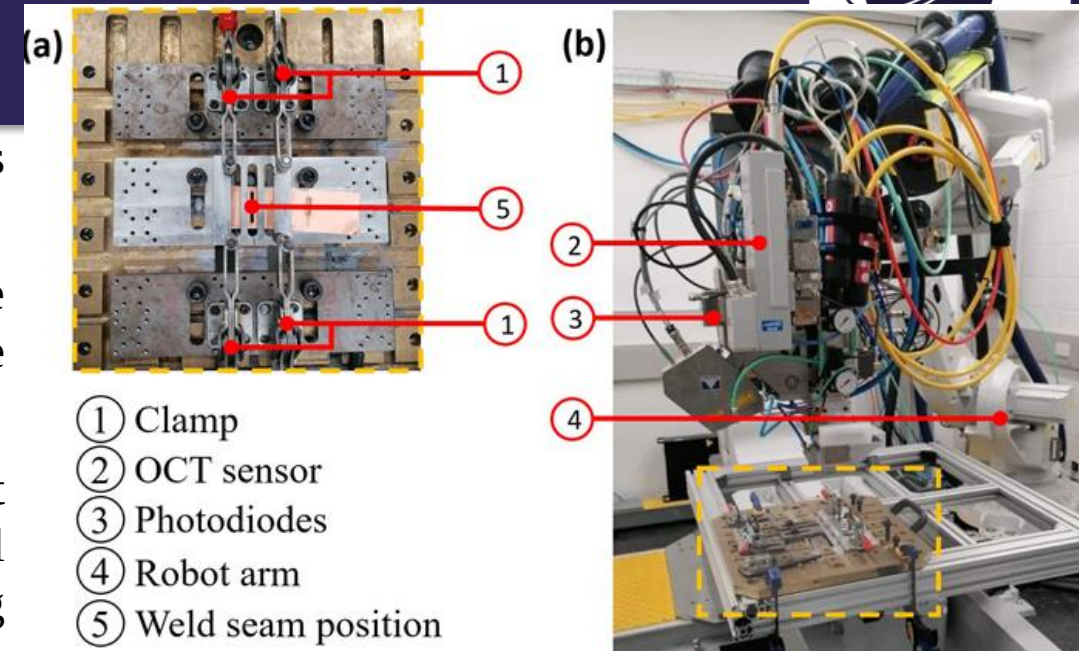


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In-situ monitoring of laser welding process

Special techniques: Optical coherence tomography

- Additionally, X-ray is restricted to temporal resolution and is less effective in detecting defects during the laser welding process.
- Optical coherence tomography (OCT) imaging is one of the intuitive methods developed by Precitec GmbH to measure the keyhole capillary depth.
- The system operates at a wavelength of 1540nm, featuring an output power and a measurement rate of up to 70kHz and achieves an axial precision of 10 μm for an adaptive penetration depth control during remote laser welding.
- Typically, X-ray imaging techniques are costly and difficult to set up, whereas OCT is similarly expensive and limited to generating keyhole depth information.

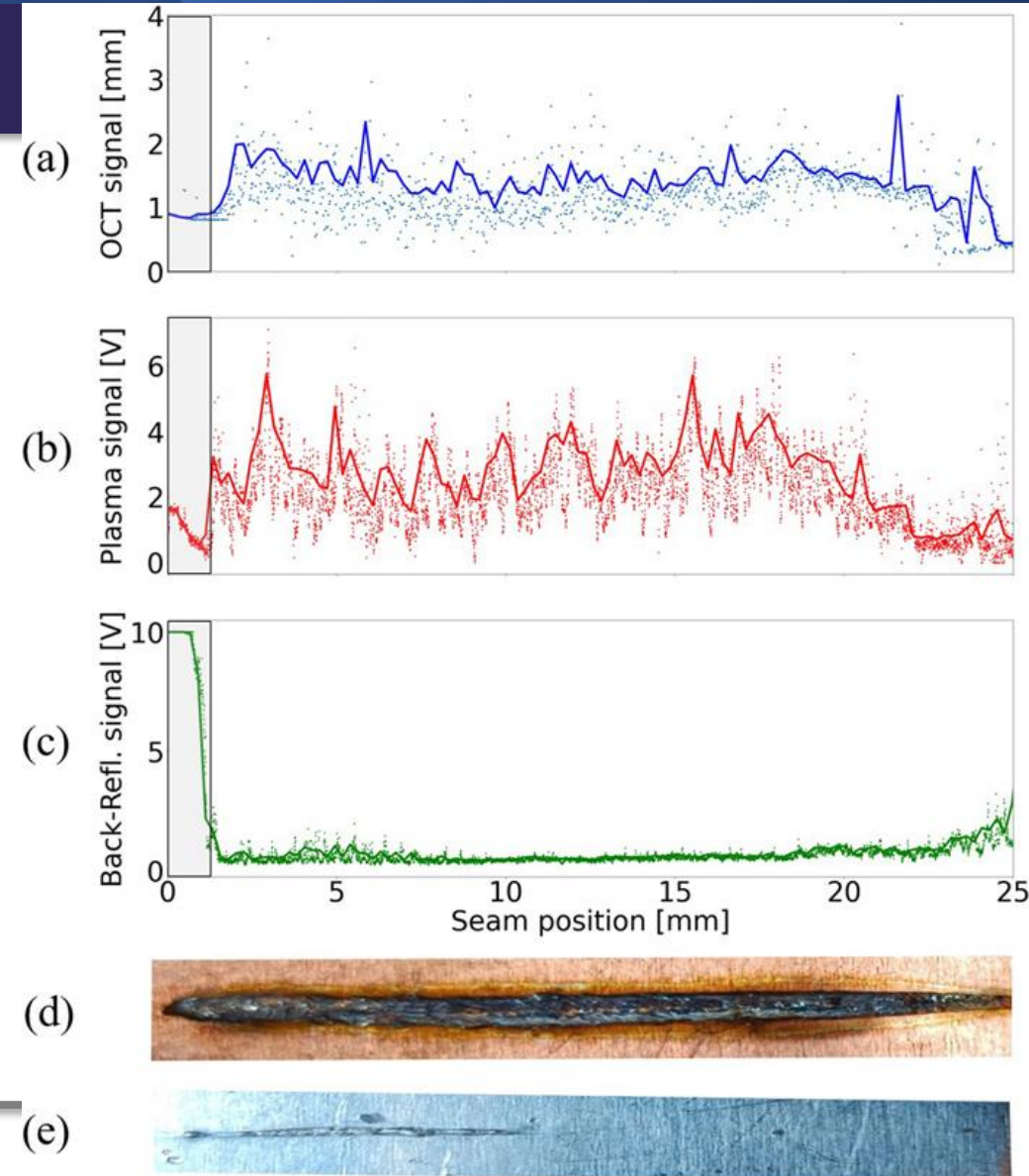


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<https://doi.org/10.1007/s40194-019-00710-7>.

In-situ monitoring of laser welding process

Special techniques: Optical coherence tomography

- Figure shows typical OCT, plasma and back-reflection signals, and top and bottom pictures of the corresponding weld. Transitional phenomena at the beginning of the welding can be noticed from the signals
- Acquired signals were processed using the percentile filtering method, to remove high-frequency disturbances from the raw data of both photodiode and OCT signals.
- Percentile filtering is based on a moving window (M_W) which determines the amount of data needed to be filtered in the same step, and percentile value (P_V) which determines the percentage of data lying under the filtered signal. M_W and P_V were determined with screening experiments showing $M_W = 50$ and $P_V = 80\%$ resulting in the highest accuracy. To remove the transient regime at the beginning (due to in-coupling of the laser with Cu) and end of the weld, the first and last 2.5 mm need to be removed from the signals.



In-situ monitoring of laser welding process

Special techniques: Optical coherence tomography

- Figure shows a typical OCT signal obtained with a power ramp of the process beam, in overlap seam welding.
- When the OCT measurement beam is correctly aligned towards the keyhole bottom, the OCT technology is capable of providing fast and accurate direct measurement of the keyhole depth.
- Assuming that the molten layer just underneath the keyhole bottom is neglectable, this approach results in a promising solution for Weld Penetration Depth Control
- OCT technology has been successfully used for continuous monitoring of weld penetration depth in a number of applications, primarily with stationary process beam and overlap seam welding.

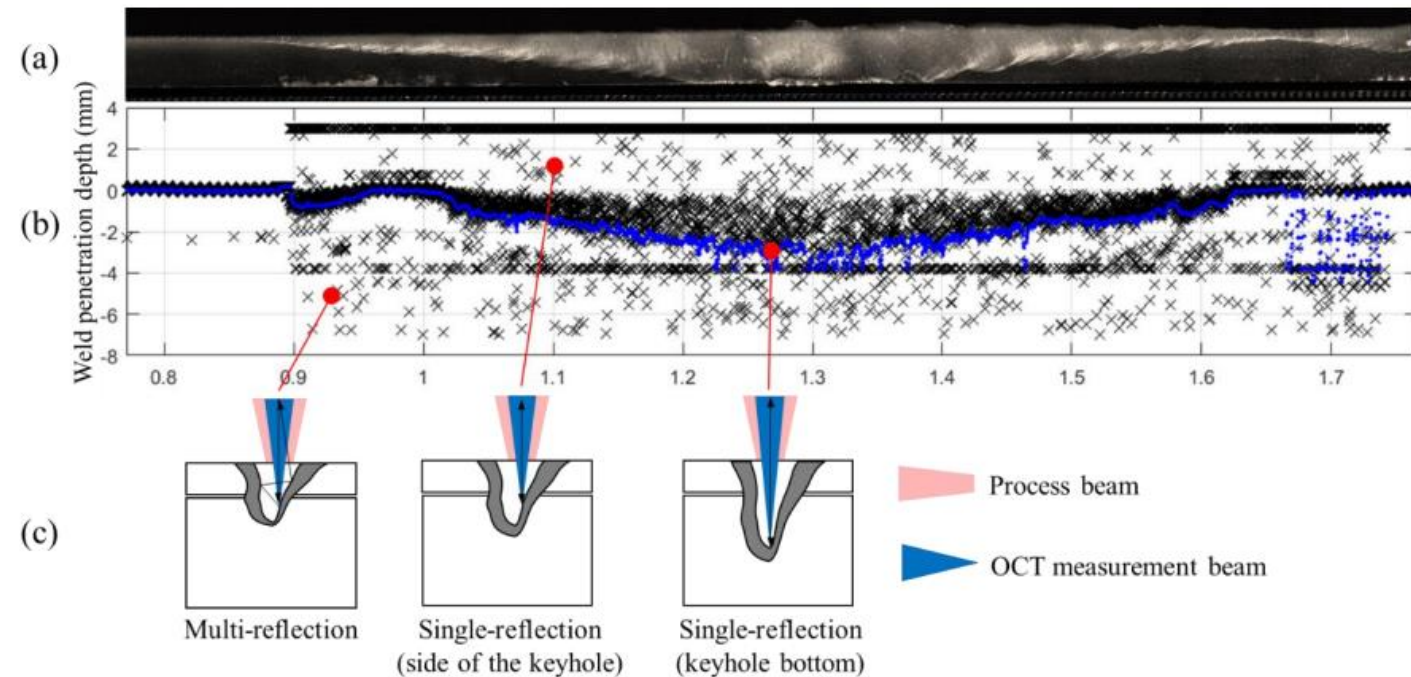
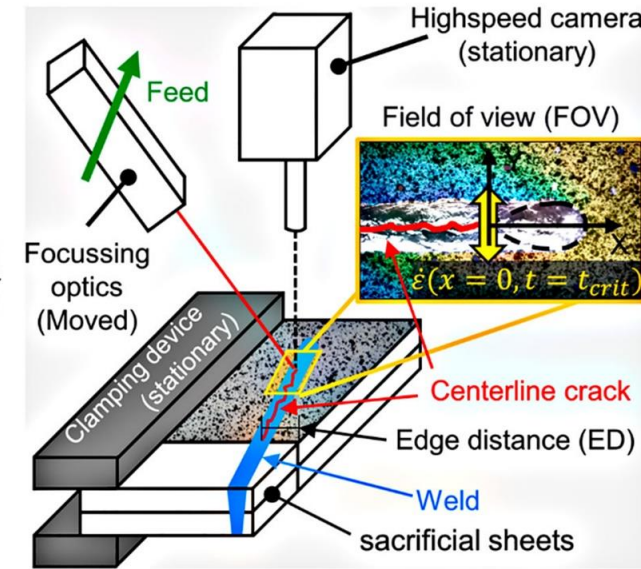
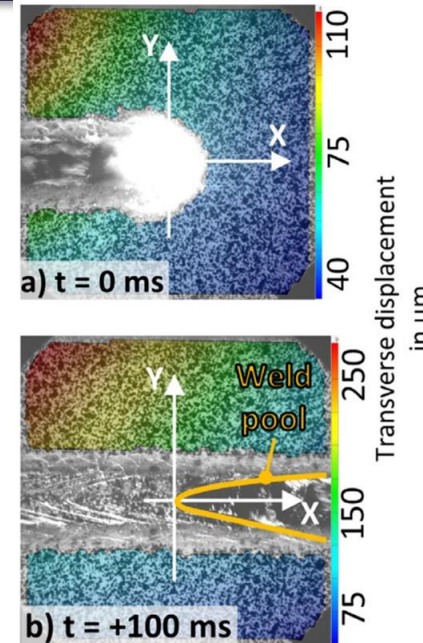


Figure 1 OCT signal interpretation: (a) longitudinal cross-section of weld; (b) raw (black cross) and processed (blue dot) OCT signal; (c) reflection modes and interpretations.

In-situ monitoring of laser welding process

Special techniques: Strain In-situ measurement for detecting cracks

- It has been understood that strain and strain rate during laser welding are crucial for detecting the formation of solidification cracks.
- The ability to measure strains close to the fusion boundary yields crucial information about the thermal strain conditions within the fusion zone, which are directly associated with the likelihood of solidification cracking during welding.
- Real-time monitoring of strain field evolution enables researchers to identify the critical strain thresholds indicative of the onset of cracking during laser welding.
- A MISO (mean in-situ observation) technique was developed to directly measure strain in the weld mushy zone by tracking small discontinuities found on the weld surface using a camera-based sensor.

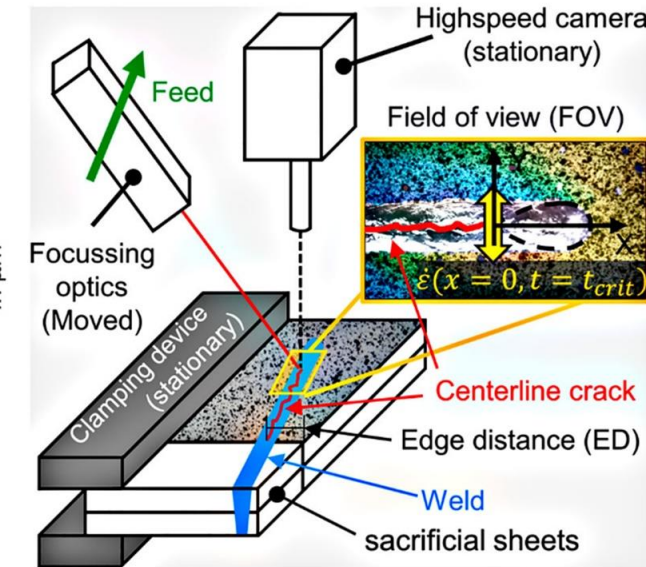
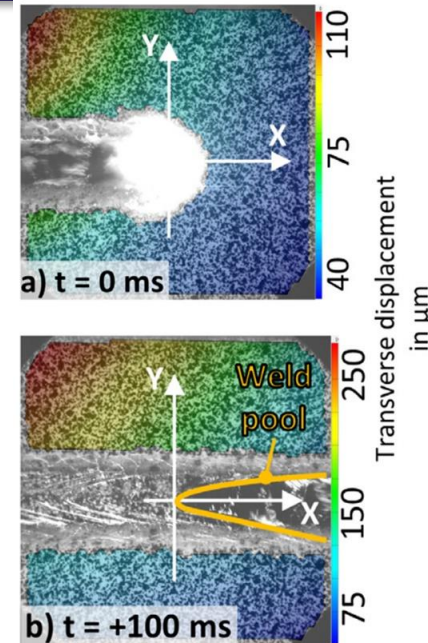


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In-situ monitoring of laser welding process

Special techniques: Strain In-situ measurement for detecting cracks

- However, the challenging optical conditions owing to the plasma fume streaks and high thermal magnifications attributed to high temperature are believed to contribute to significant measurement errors in the MISO technique.
- Despite strain gauges and induction types being the most established sensors to measure strains, they can only be used outside the fusion zone.
- They cannot be used near the immediate vicinity of the molten pool because of the high-temperature cycles during welding.

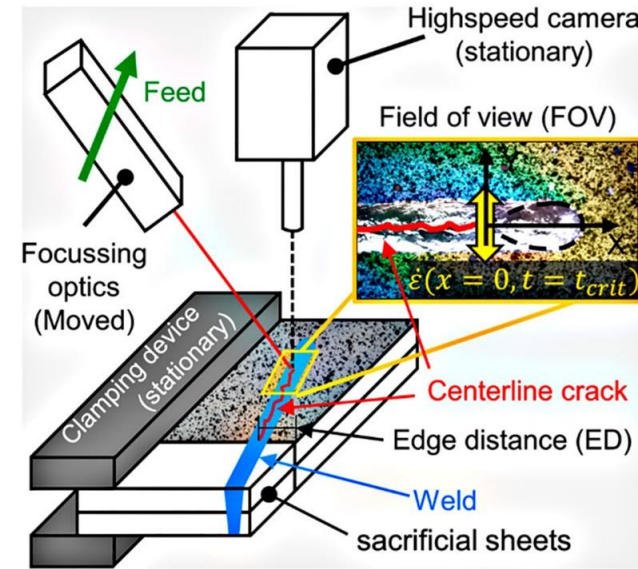
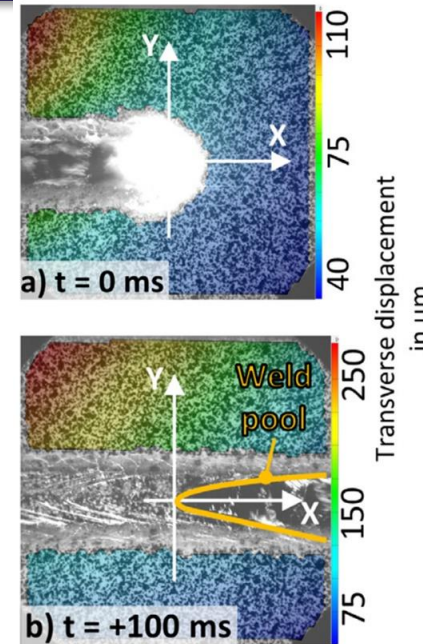


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In-situ monitoring of laser welding process

Special techniques: Digital Image Correlation (DIC)

- In recent studies, contactless measurement techniques such as image correlation techniques have been successfully implemented to measure strains around the molten pool.
- A study investigated the impact of process parameters on cracking and employed the Digital Image Correlation (DIC) technique using the GOM software to measure the critical strains produced on either side of the weld as depicted in Figure.
- Despite these techniques being capable of measuring strain around the fusion zone, they are unable to directly measure the thermal contraction and shrinkage strains on the weld surface or within the fusion zone, which are crucial for detecting cracks during the welding process



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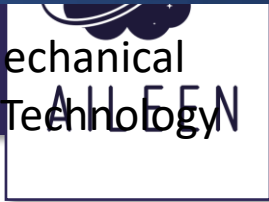
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