End Sem :- 29th Apr - 5-8PM (L19-20)

Welding Technology: ME692

Syl:- After Midsem syl. (after Lec 9) 42%

Instructor: Virkeshwar Kumar

NL1-115R, Manufacturing Science Lab

Department of Mechanical Engineering

IIT Kanpur

Email: virkeshwar@iitk.ac.in

Phone: 0512-259-2334

Format:- Derivation + N. P. + 10 O.P.

Hand written cheat sheet allowed → one A4 sheet

1 M.H.P + (Thick plate, Thin plate, C.R., Adam's)

2 Thermo: (Pure, Binary)

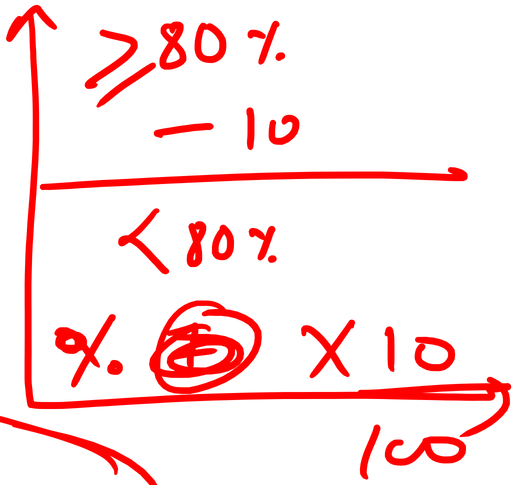
3 Solidification

4 Adv in welding

5 Stress

6 Defects & measurement.

Advancement in Welding



arc:- 5 mm/sec

MPW

~~EMP~~

EBW

30mm/ sec

Underwater Welding

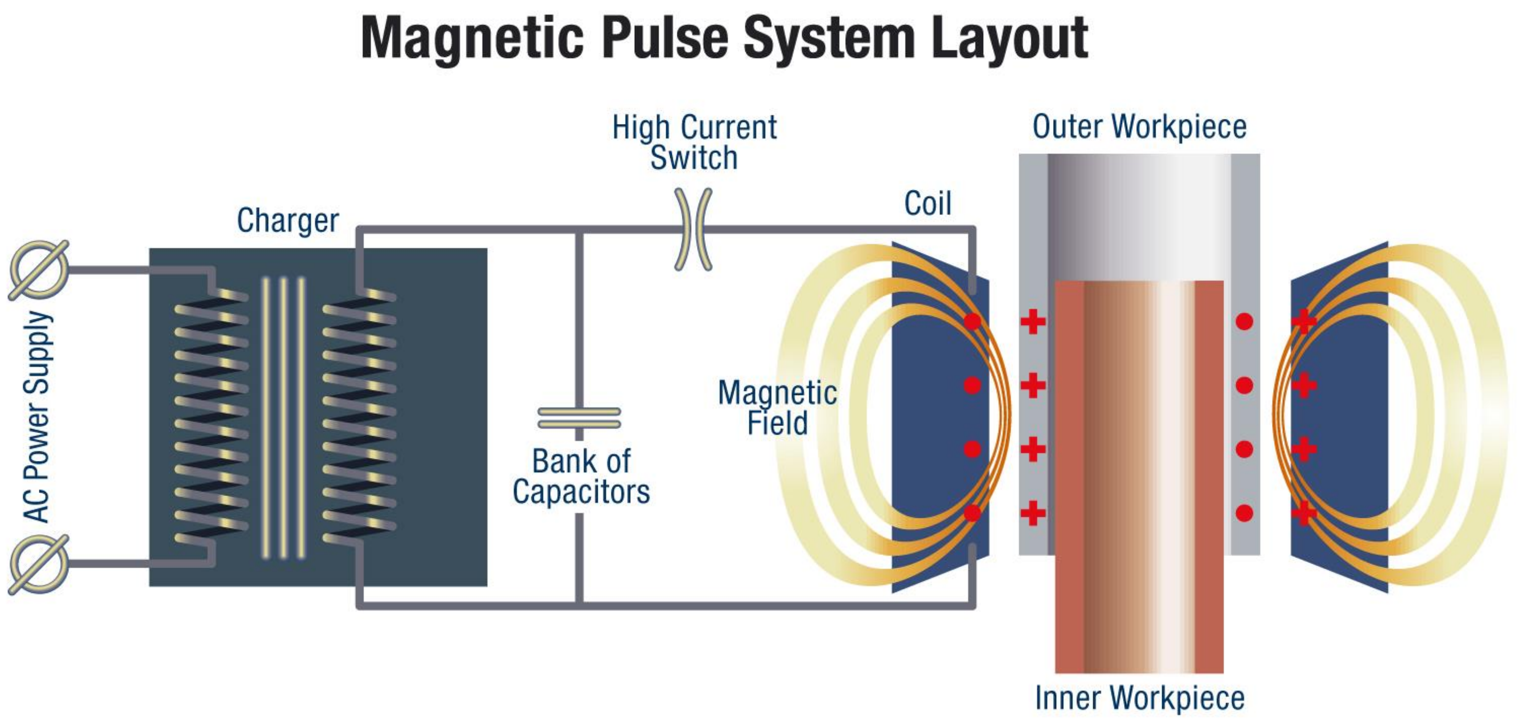
LBW

dissimilar material

Additive Manufacturing

Magnetic Pulse Welding (MPW)

- ✓ Solid state, non-fusion, cold process
- ✓ Weld by high velocity impact (300 m/s)- High velocity forming process
- ✓ Metals briefly act like liquid
- ✓ Joining dissimilar materials, esp. highly conductive
- ✓ No HAZ



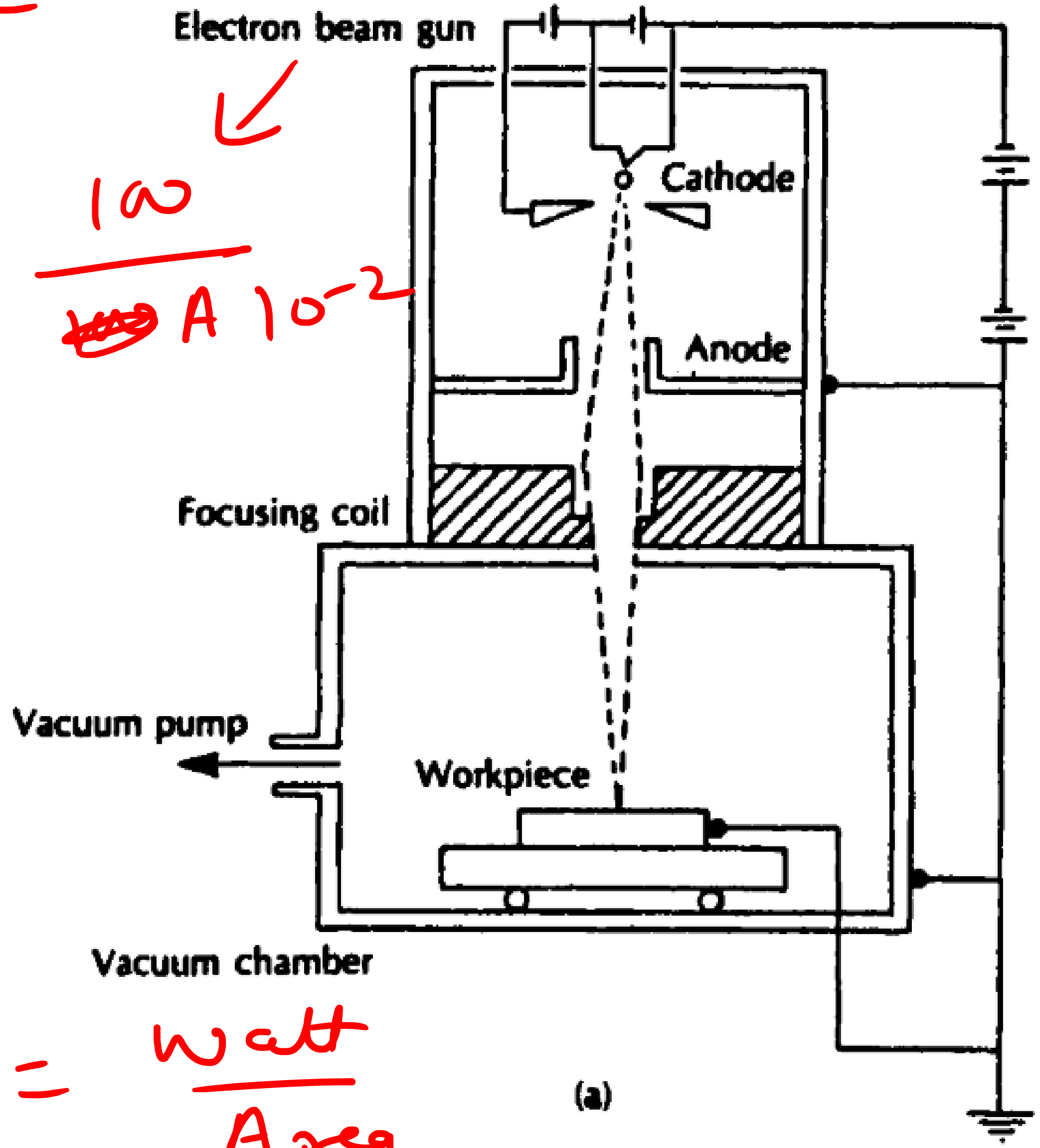
Magnetic Pulse Welding (MPW)

https://www.youtube.com/watch?v=DAddzH6lutk&ab_channel=BmaxChannel

https://www.youtube.com/watch?v=UGHtrLhqQ9w&ab_channel=BmaxChannel

Electron Beam Welding (EBW)

$\frac{\pi}{4} 0.5^2$ $\frac{\pi}{4} 5^2 \times 10^{-2}$



$\frac{100}{\cancel{100}\ A\ 10^{-2}}$

$A = \frac{\pi}{4} 5^2$

arc

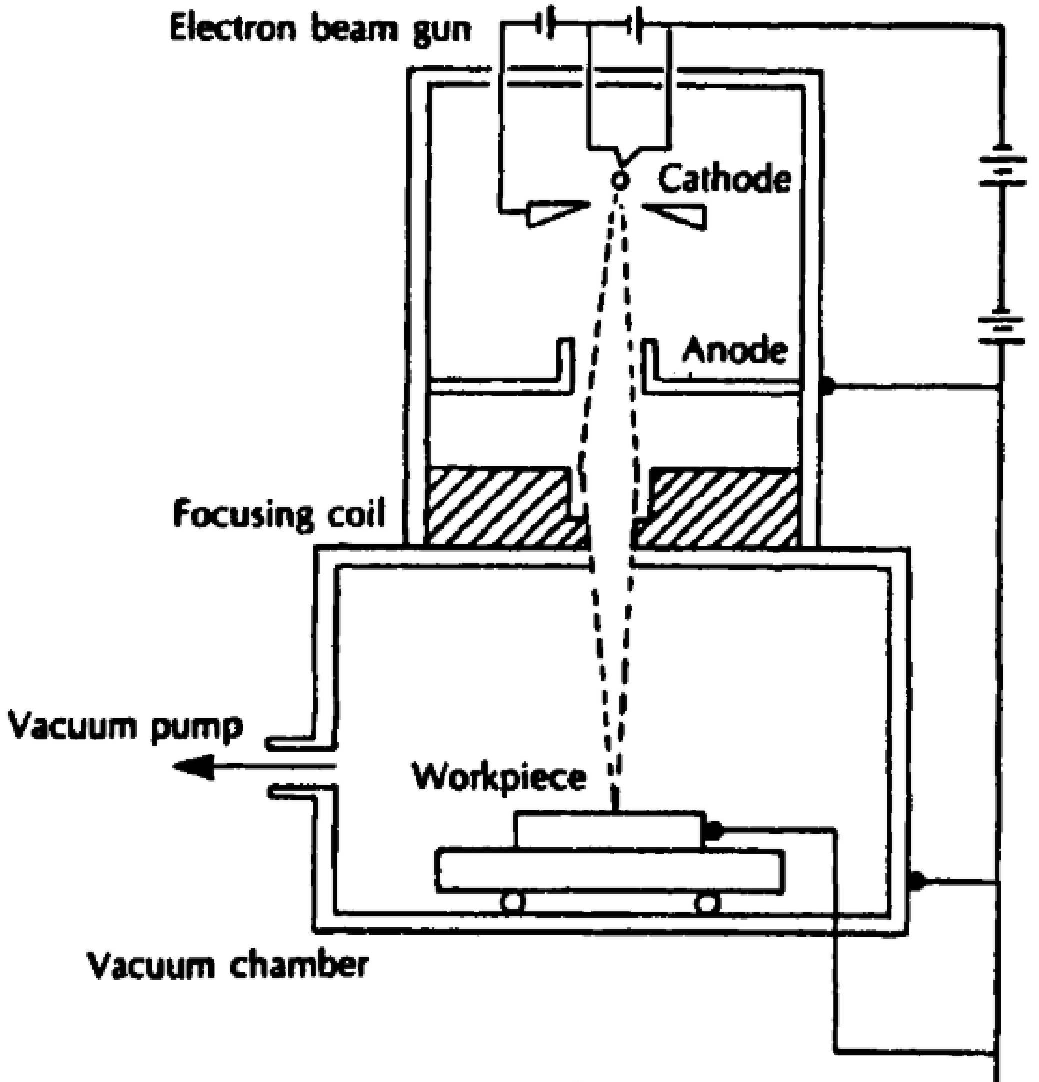
Energy density = $\frac{\text{watt}}{\text{Area}}$

$\frac{100}{A}$

=

Electron Beam Welding (EBW)

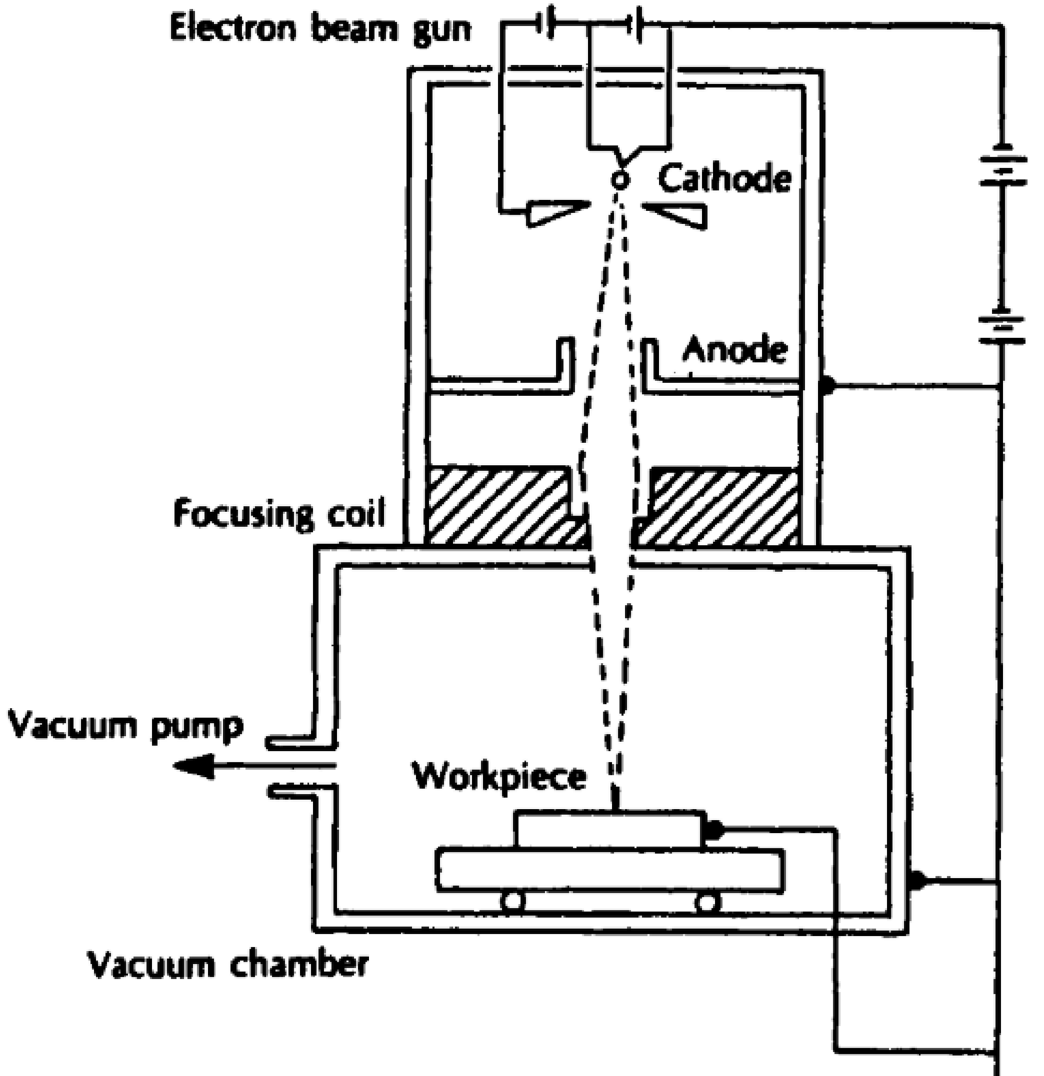
- ✓ Electron beam is the energy source for melting the metals.
- ✓ As the filament is negatively charged, it emits electrons which are accelerated by an electric field.
- ✓ These electrons go through the anode and are focused (0.3 ~ 0.8 mm diam.) by an electromagnetic coil on the w/s surface with a high power density (~ 10^{10} W/m^2).
- ✓ High-intensity beam forms a deep penetrating keyhole.



(a)

Electron Beam Welding (EBW)

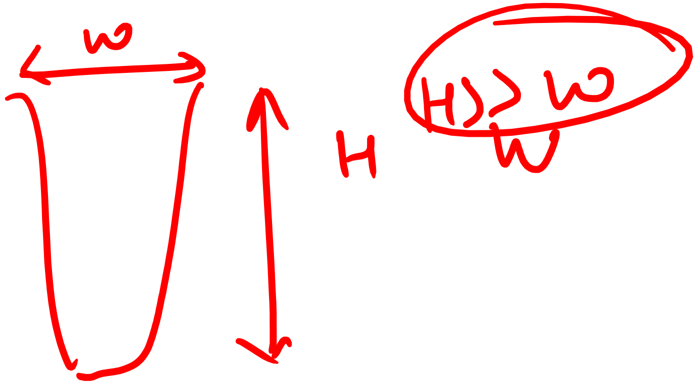
- ✓ Beam is focused (ø 0.8 - 3.2 mm) + can produce high temperatures but requires vacuum (10^{-3} – 10^{-5} atm) to prevent electrons from interacting with atoms/molecules in the atmosphere
- ✓ Imposes size restrictions (but vacuum cleans surfaces)+ slow changeover – hence expensive.
- ✓ Good for difficult-to-weld materials; Zr, Be, W
- ✓ Very narrow HAZ, deep penetration,
- ✓ high power + heat, deep, narrow welds, high speeds
- ✓ **No filler, gas, flux, etc.**



(a)

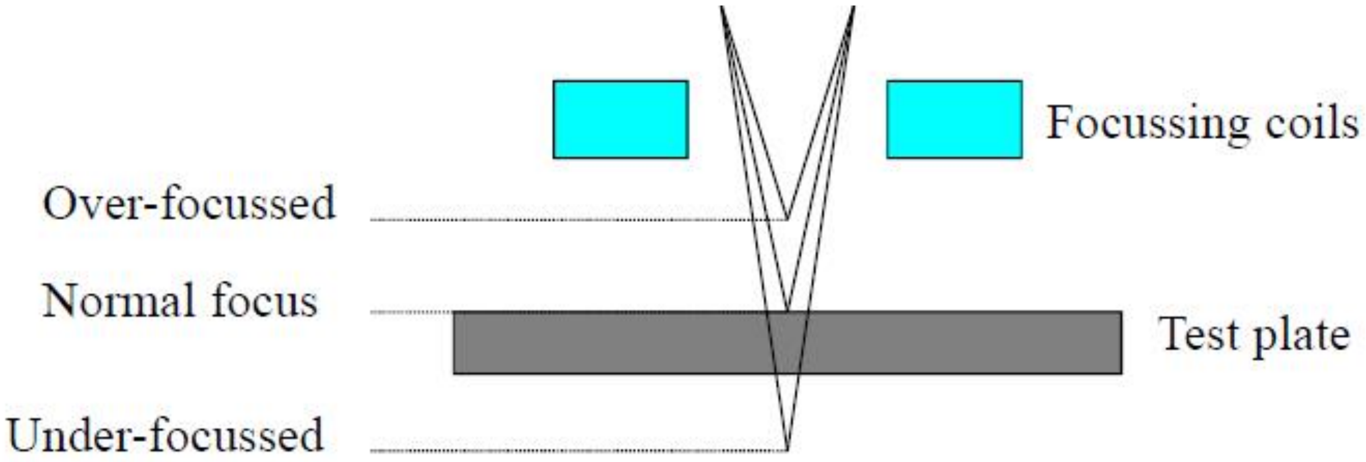
Electron Beam Welding (EBW)

- ✓ Joints must fit together very well before welding and tend to be simple straight or square butt joints
- ✓ Filler metal can be added as wire for shallow welds or to correct underfill in deep penetration welds

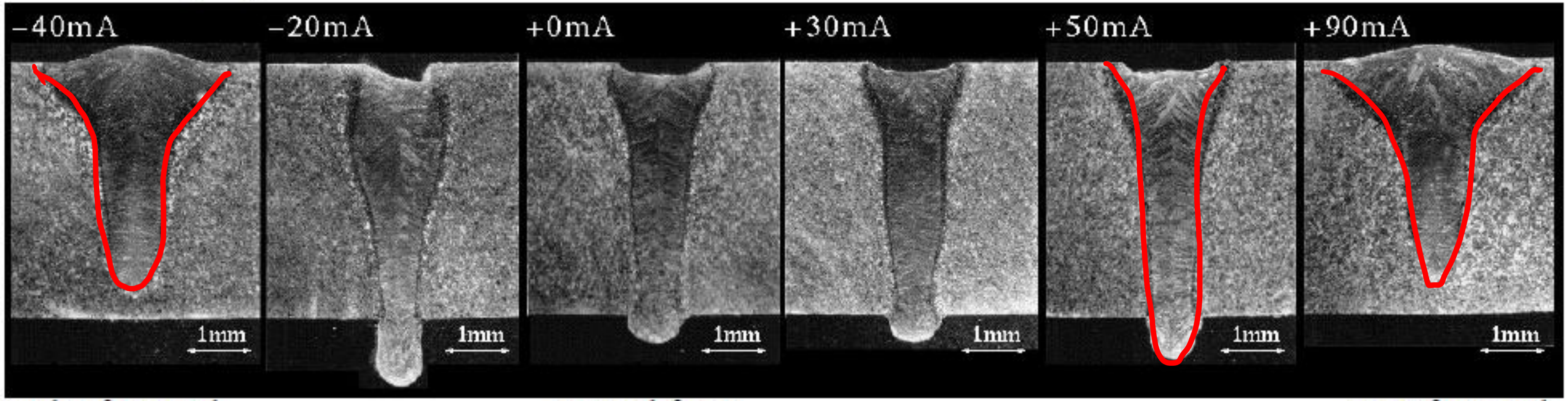


- ✓ Usually used in keyhole mode
- ✓ Electron absorption in materials is high, so transfer efficiency is high (>90%)
- ✓ High depth-to-width ratios produced (>10:1 possible)
- ✓ Low distortion and high reproducibility

Effect of Beam Defocus (EBW)



Metallographic sections



under-focussed

normal focus

over-focussed

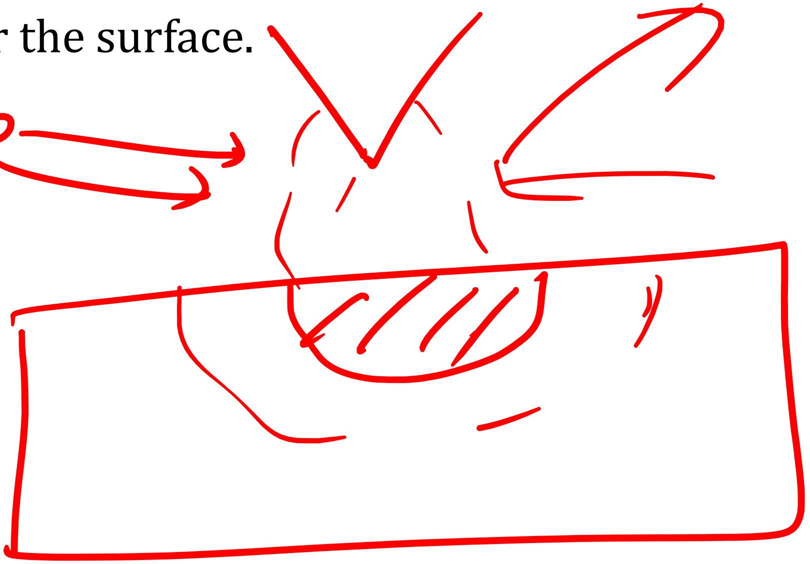
Conduction mode

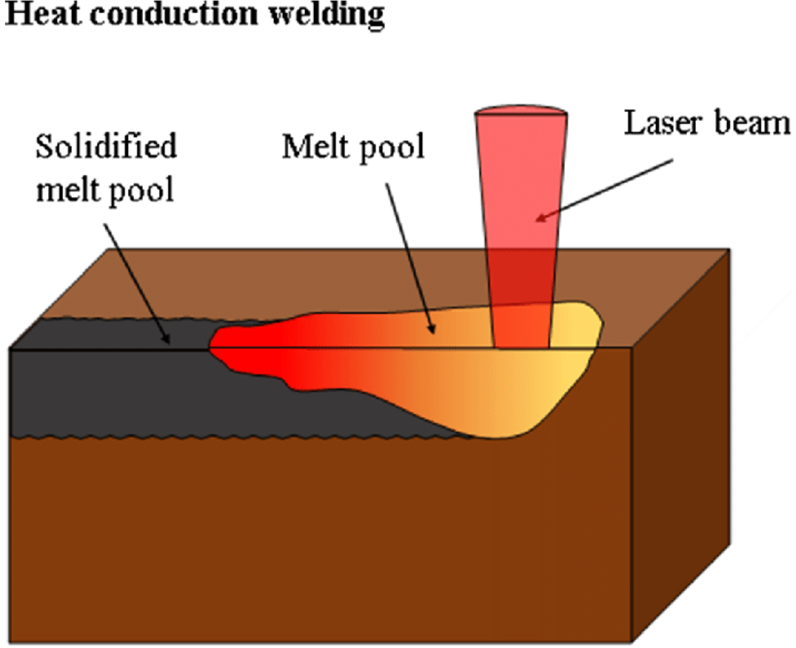
- ✓ If the rate at which energy is being deposited **exceeds** the rate at which heat is being conducted away, the temperature will rise to eventually cause melting and produce a fusion weld.

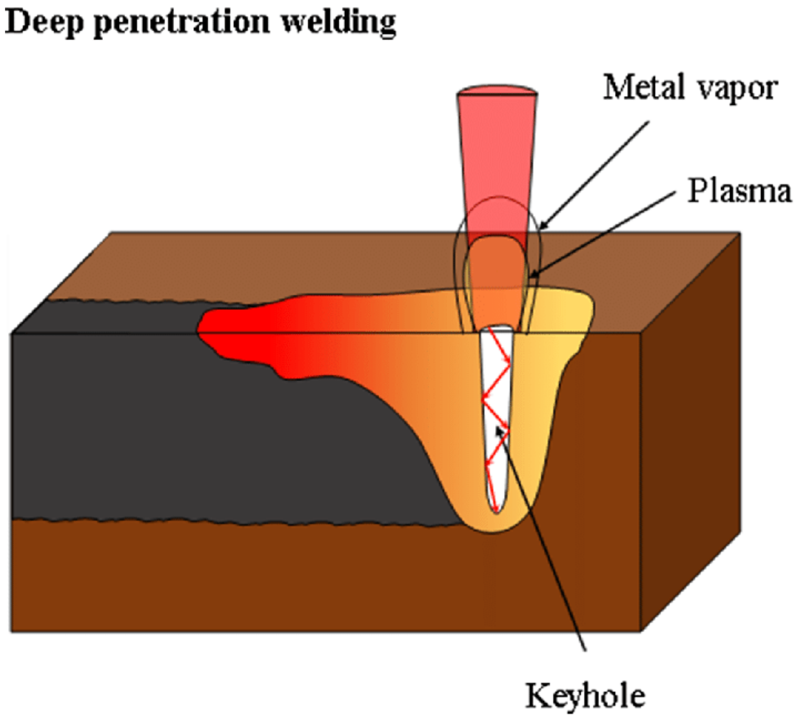
- ✓ This mode of energy deposition and weld production is called the **melt-in mode or the conduction mode**.

- ✓ In the melt-in or conduction mode, the temperature is maximum at the point of deposition, on or near the surface.

100% → 30







Keyhole mode

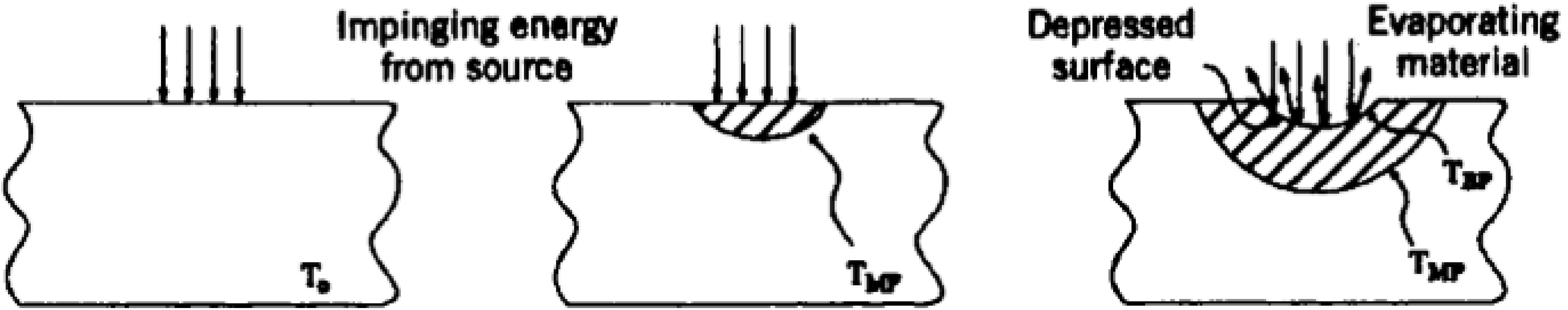
- ✓ If the density of the energy coming from a source is high enough, the rate at which it is deposited **greatly exceeds** the rate at which it is lost by being conducted into the workpiece(s).
- ✓ The material at the point of deposition rises in temperature not just to the melting point, but well above that.
- ✓ The temperature can rise to the boiling point, converting liquid to vapor, superheating the vapor.
- ✓ When this occurs, the energy source is said to be operating in the **keyhole mode**.

$$Q(J) = \rho V C_p \Delta T$$

Initial deposition of impinging energy on the surface

Surface heating and inward propagating of heat to cause melting anywhere T> Tm;

Continued inward propagation of heat to raise a larger volume of material to above Tm, and elevation of temperature near the surface to above T_{BP}, causing vaporization and a downward force on the liquid;



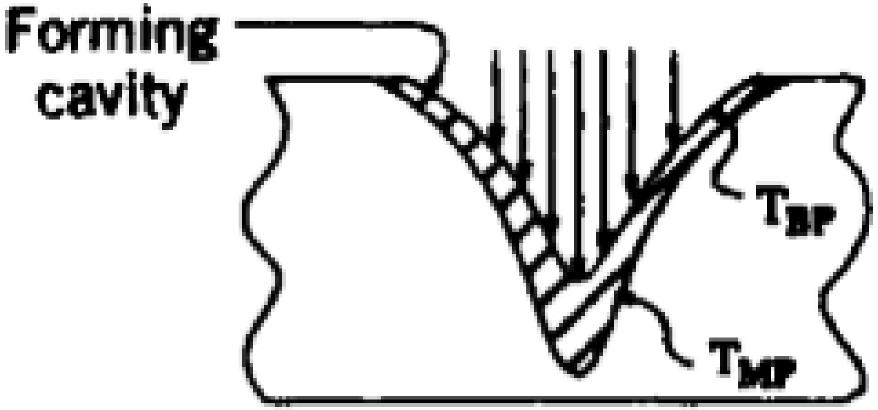
Keyhole mode

- ✓ Formed vapour (expand and less dense) moves upward away from the surface, and produces a reaction force that presses the melt downward and sideways.

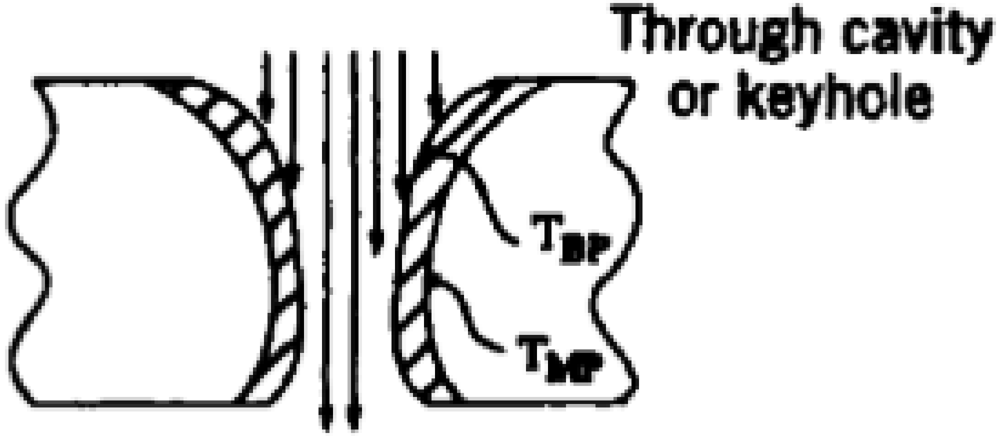
- ✓ The result is a depression that permits additional photons (from a laser beam), electrons (from an electron beam), or electrons and ions (from a plasma arc) to impinge upon fresh material, which is then heated in the same way.

- ✓ The depression becomes larger and transforms to a keyhole, the entire central core of which consists of vapor surrounded on all sides by an envelope of liquid.

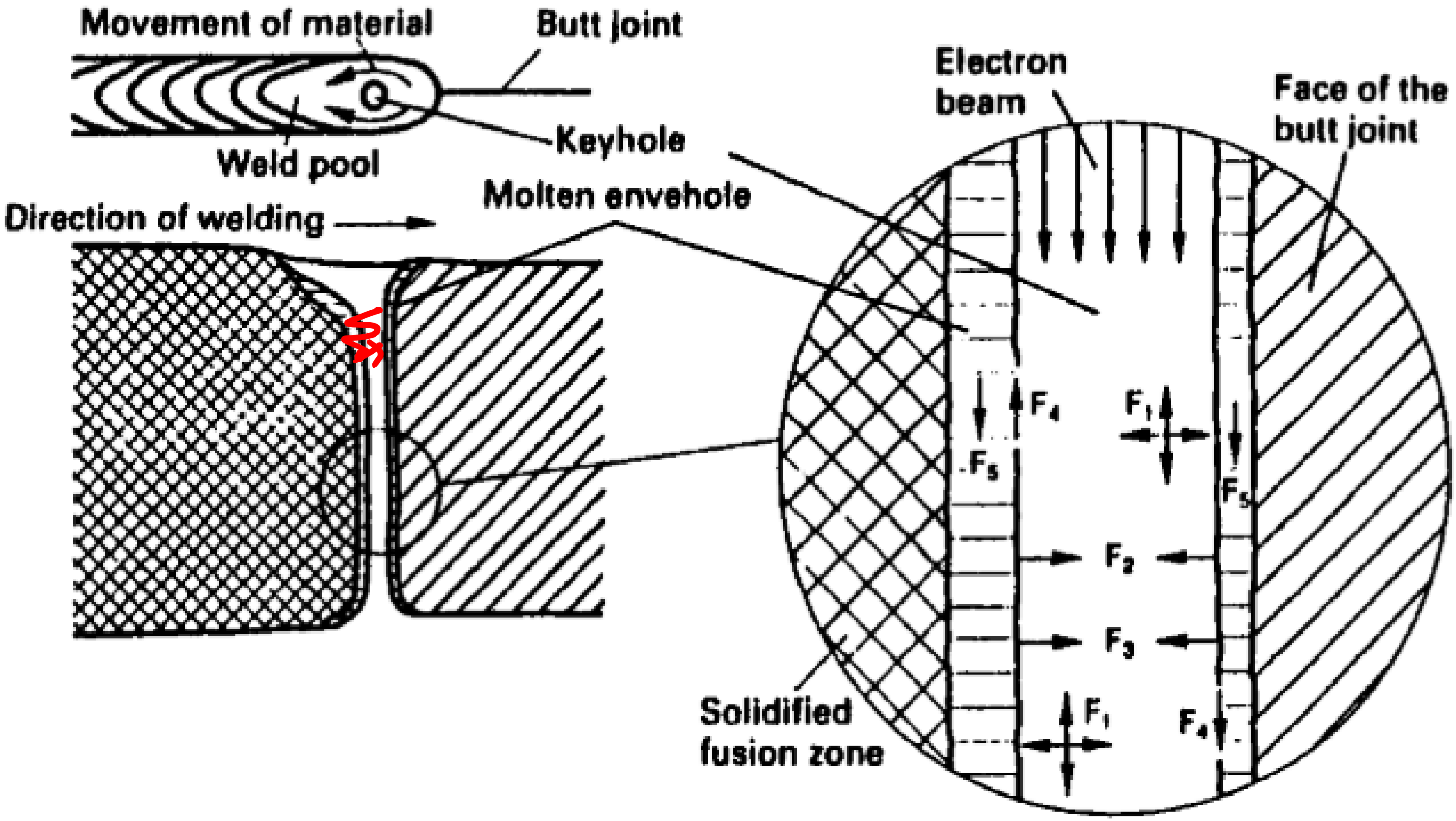
Continued deposition of heat, increased vaporization and greater depression of liquid, and increased growth of melted volume;



Eventual penetration of vapor cavity through thickness to produce a keyhole of vapor surrounded by molten material



Keyhole mode



Keyhole mode EBW

F_1 = Vapour pressure

F_2 = Force resulting from surface tension

F_3 = Hydrostatic pressure

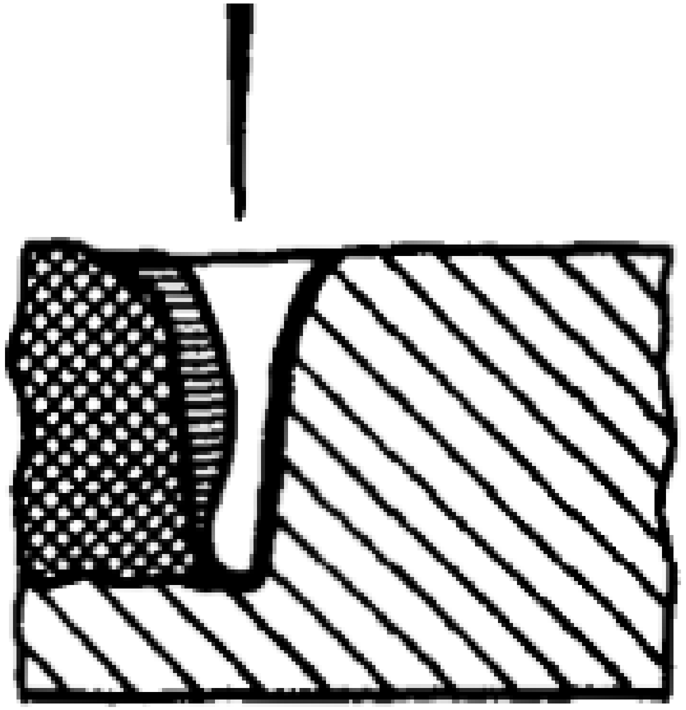
F_4= Frictional force from the escaping metal vapour

F_5 = Weight of the molten liquid.

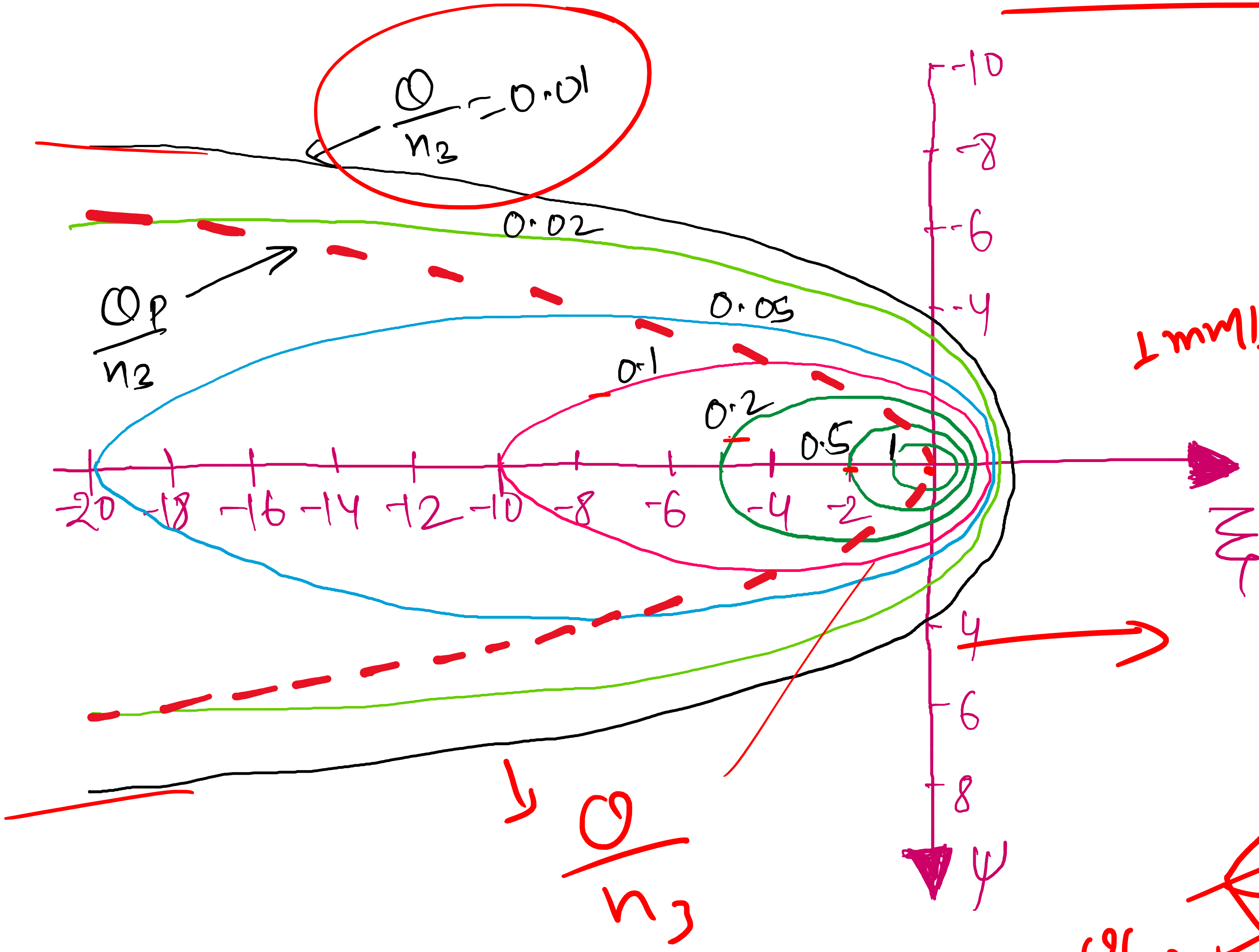
Keyhole mode

- ✓ While welding proceeds with a keyhole, hydrodynamic forces (particularly from gravity) intermittently cause the molten envelope surrounding the vapor cavity or keyhole to collapse.
- ✓ When this occurs, the stream of incoming energy is momentarily blocked, penetration is momentarily lost, and defects in the form of voids can be left entrapped.

Possibility of interruption of beam penetration, with possible formation of voids, during keyhole welding with an electron beam.



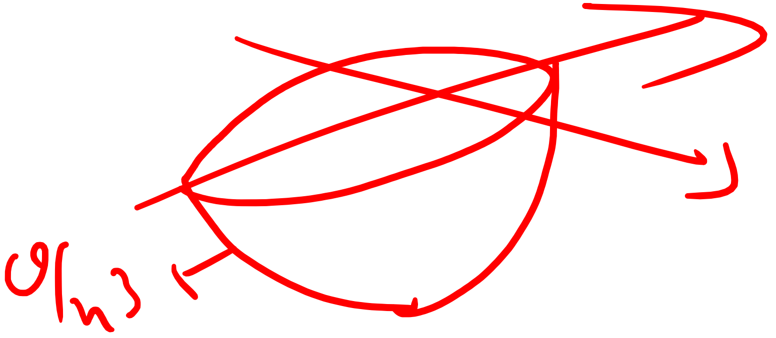
Moving Heat Sources: thick plate: V high



$$\eta_3 = \frac{q_0 V}{4\pi\alpha^2 \Delta H}$$

1 mm/s → For $\theta = 1$
$n_3 = 1$
arc
$n_3 = \frac{\theta}{n_3} = 1$

n_3 → 100 mm/s EBW
$\frac{\theta}{n_3} = 0.01$



Moving Heat Sources: thick plate: V_{high}

- ✓ Isotherms behind the heat source become increasingly elongated as the arc power q_0 and the welding speed V increase **(Θ/η_3 decreases).**

$\frac{\Theta}{\eta_3}\downarrow$ de

- ✓ Limiting case: q_0 and V approaching very high, and q_0 /V has finite value
- ✓ The isotherms will degenerate into surfaces which are parallel to the welding *x* direction.
- ✓ In a short time interval *dt*, the amount of heat released per unit length of the weld is equal to $\frac{dQ}{dx} = \frac{q_0 dt}{V dt} = \frac{q_0}{V}$

$\rightarrow$ Tot.

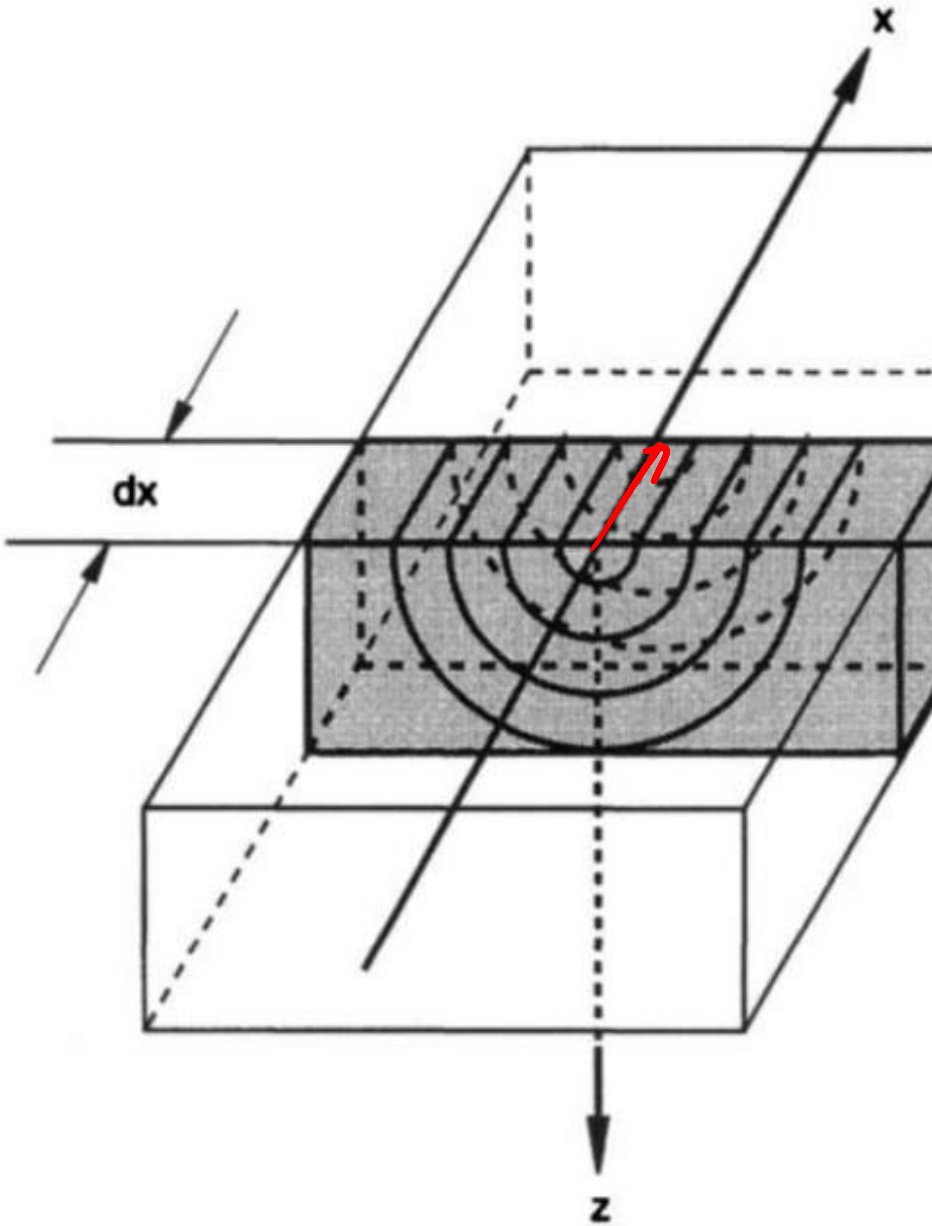
$$\eta_3 = \frac{q_0 V}{4\pi\alpha^2 \Delta H}$$

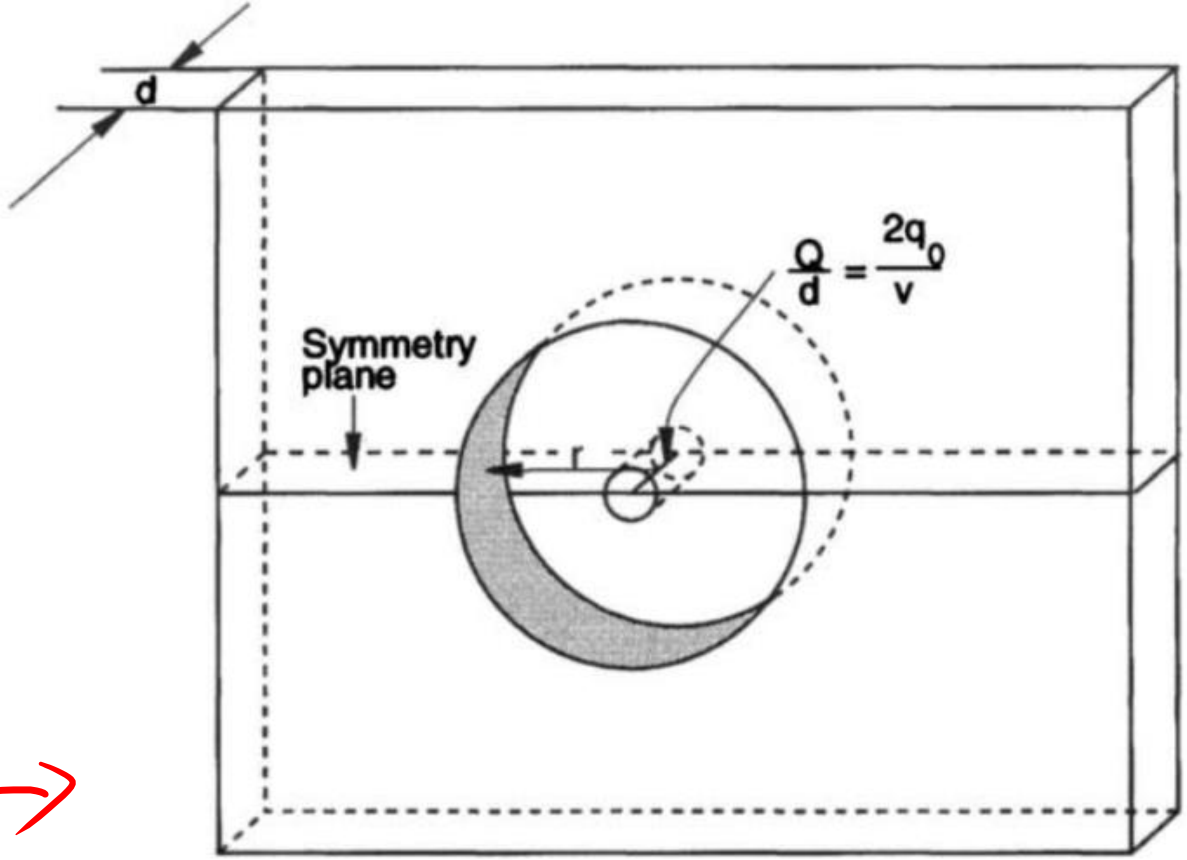
Moving Heat Sources: thick plate: V_{high}

- Low-thermal Gr. in welding direction
- Amount of heat will remain in a slice of thickness dx
- Symmetry isotherms in the y-z plane are semi-circles,
- The situation becomes identical to the temperature field around a line instantaneous heat source in a thin plate.

$$T - T_\infty = \frac{E_0}{4\pi\alpha\rho C_p L \cancel{x} t} \exp\left(-\frac{r^2}{4\alpha t}\right)$$

Moving Heat Sources: thick plate: V $_{high}$





$$\eta_3 = \frac{q_0 V}{4\pi\alpha^2 \Delta H}$$

Moving Heat Sources: thick plate: V_{high}

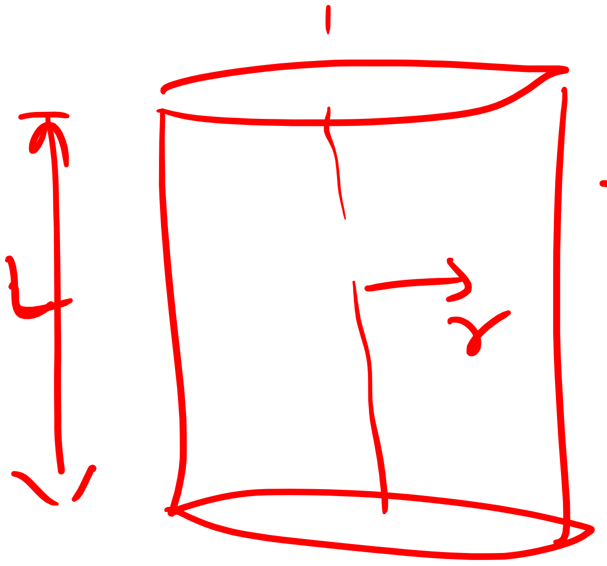
line heat source → integration problem

$$T = T_0 + \frac{E_0}{\rho c\, 4\pi\alpha t L} e^{-\frac{r^2}{4\alpha t}}$$

E_0 energy

$$\frac{dE_0}{dx} = \frac{2q_0}{V}$$

$$T = T_0 + \frac{\frac{2q_0}{V}}{\rho c\, 4\pi\alpha t} e^{-\frac{r^2}{4\alpha t}}$$



has release at centre

Moving Heat Sources: thick plate: V_{high}

$$T = T_0 + \frac{\frac{\cancel{2} q_0}{V}}{2\cancel{4}\pi \alpha \rho c\, t} e^{-\frac{r^2}{4\alpha t}}$$

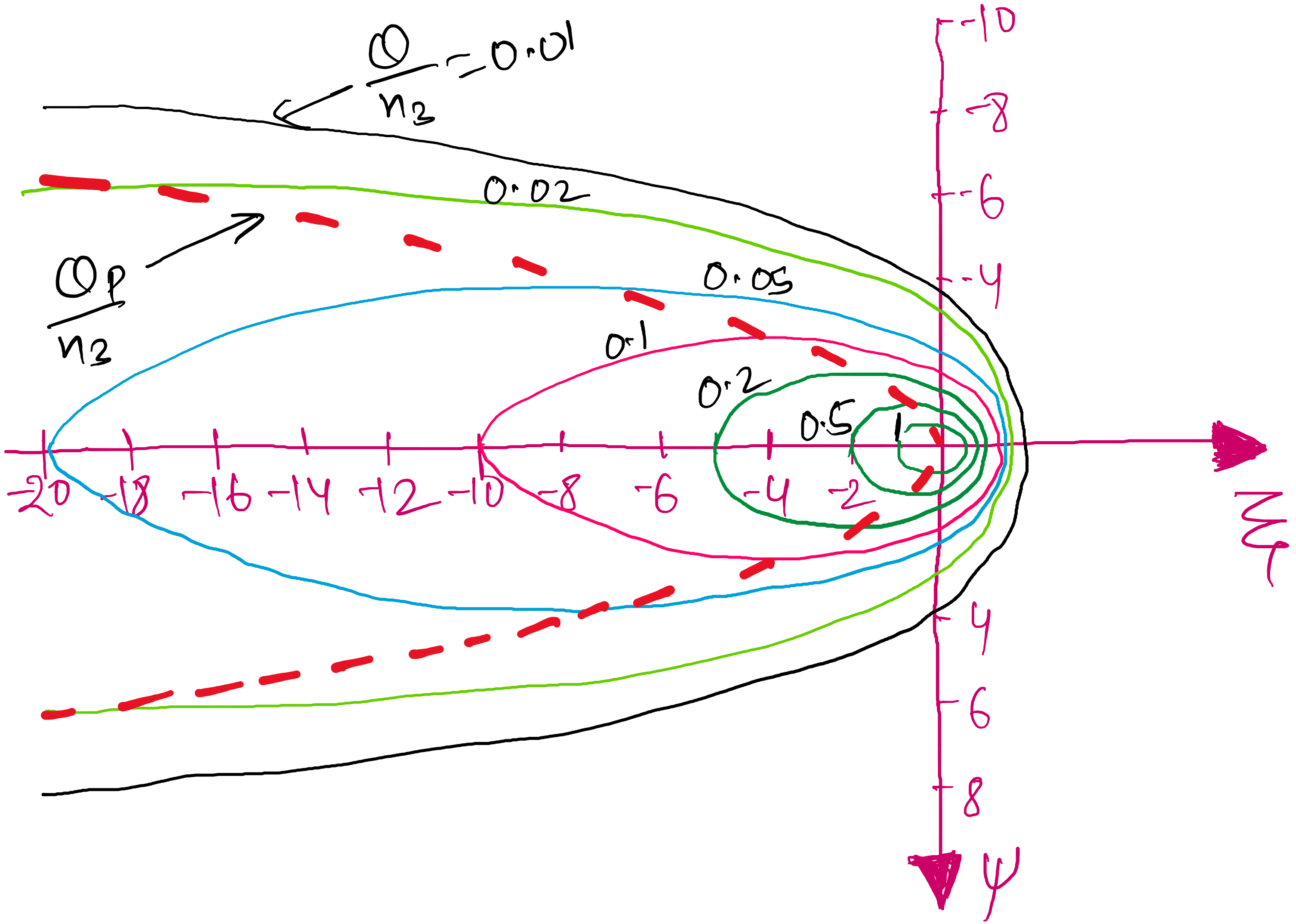
$$\alpha = \frac{k}{\rho c}$$

$$\boxed{k = \rho c \alpha}$$

$$= T_0 + \frac{q_0/v}{2\pi k t} e^{-\frac{r^2}{4\alpha t}}$$

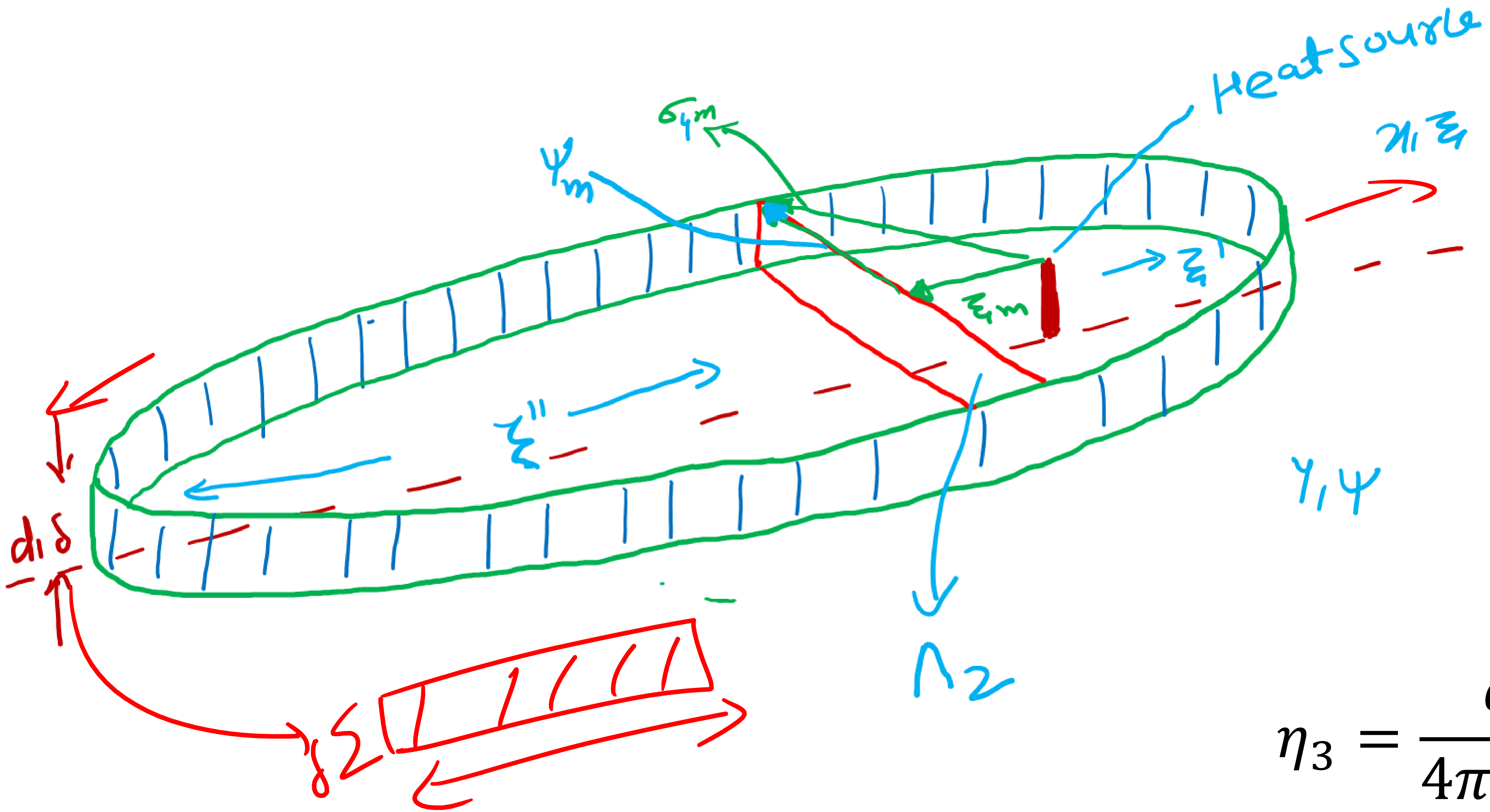
$$\boxed{T = T_0 + \frac{(q_0/v)}{2\pi k t} e^{-\frac{r^2}{4\alpha t}}}$$

Moving Heat Sources: thin plate: V $_{high}$



$$\eta_3 = \frac{q_0 V}{4\pi\alpha^2 \Delta H}$$

Moving Heat Sources: thin plate: V_{high}



$$\eta_3 = \frac{q_0 V}{4\pi\alpha^2 \Delta H}$$

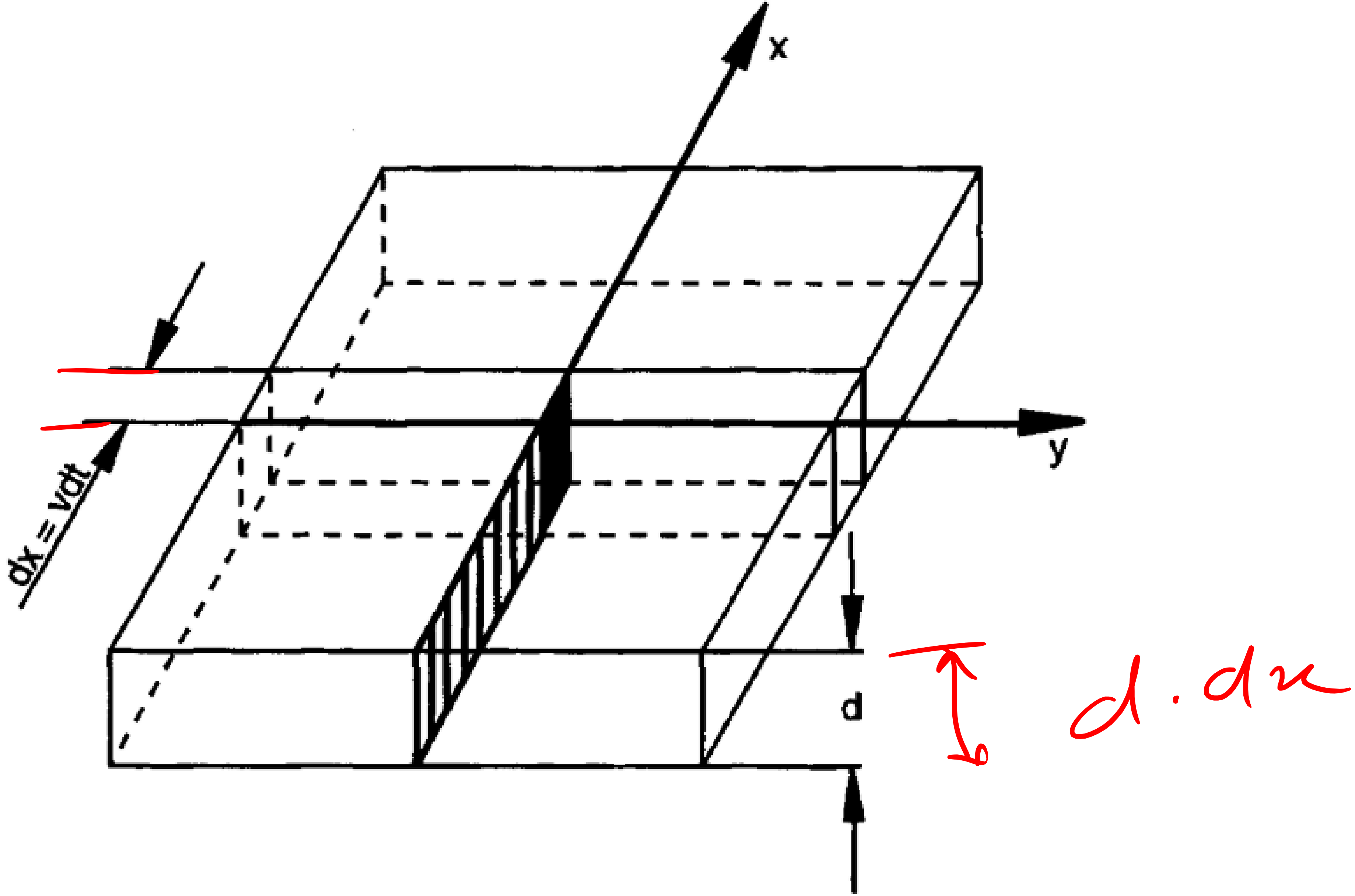
Moving Heat Sources: thin plate: V $_{high}$

- ✓ Isotherms behind the heat source become increasingly elongated as the arc power q_0 and the welding speed V increase **($\theta\delta/\ \eta_3$ decreases).**
- ✓ Limiting case: q_0 and V approaching very high, and q_0 /V has finite value
- ✓ The isotherms will degenerate into surfaces which are parallel to the welding *x* direction
- ✓ In a short time interval *dt*, the amount of heat released per unit area of the weld is equal to

$$\frac{dQ}{dA} = \frac{q_0 dt}{d.dx} = \frac{q_0}{d.V}$$

$$\frac{dQ}{dA} = \frac{q_0}{d.V} \qquad \eta_3 = \frac{q_0 V}{4\pi\alpha^2 \Delta H}$$

Moving Heat Sources: thin plate: V_{high}



Moving Heat Sources: thick plate: V_{high}

- ✓ Low-thermal Gr. in welding direction
- ✓ Amount of heat will remain in a rod of constant cross-sectional area
- ✓ Under such conditions the mode of heat flow becomes essentially one-dimensional (line instantaneous heat source)

$$T - T_o = \frac{Q / A}{\rho c (4 \pi a t)^{1/2}} \exp(-x^2 / 4at)$$

Moving Heat Sources: thin plate: V_{high}

instantaneous heat source profile
for plane source

$$\boxed{T = T_o + \frac{Q}{A(4\pi\alpha t)^{1/2}\rho c} e^{-\frac{x^2}{4\alpha t}}}$$

$$\frac{q_o}{d.V}$$

$$\frac{dQ}{dA} = \boxed{T = T_o + \frac{q_o}{dV(4\pi\alpha t)^{1/2}\rho c} e^{-\frac{y^2}{4\alpha t}}}$$

dV: thickness of plate

Moving Heat Sources: thin plate: V_{high}

Laser Beam Welding (LBW)

- ✓ Laser beam welding is a thermal material joining process that utilizes a high energy, coherent light beam to join metallic and non-metallic product.

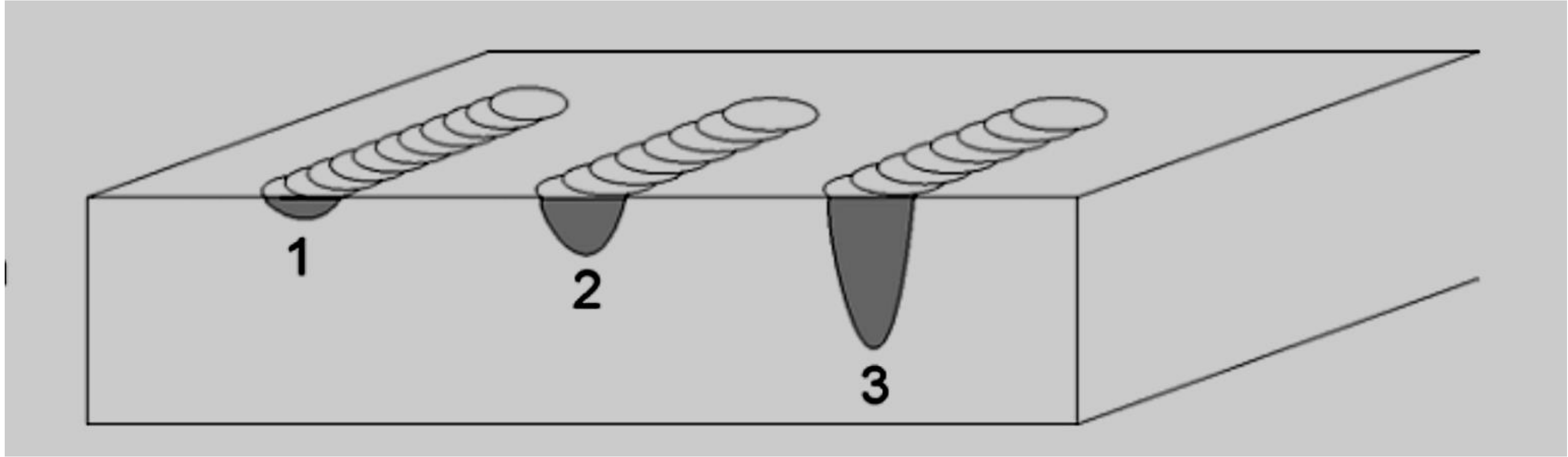
- ✓ The weld is formed as the intense laser light rapidly heats the material-typically calculated in milli/nano-seconds.

- ✓ There are typically three types of welds:
    - ✓ Conduction mode
    - ✓ Penetration or keyhole mode.

Laser Beam Welding (LBW)

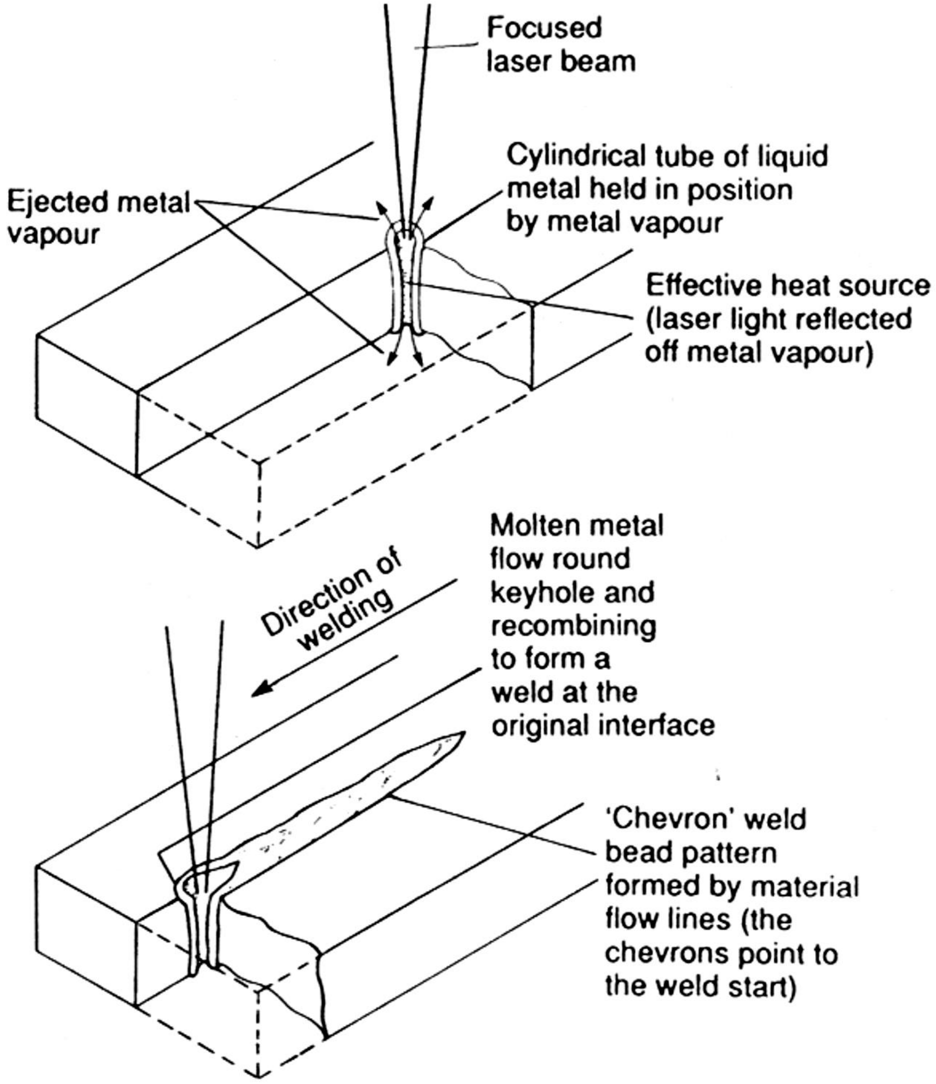
- ✓ The weld is formed as the intense laser light rapidly heats the material-typically calculated in milli-seconds.

- ✓ There are typically three types of welds:
  - ✓ Conduction mode
  - ✓ Conduction/penetration mode
  - ✓ Penetration or keyhole mode.



Laser Beam Welding (LBW)

- ✓ Laser is heat source 10 kW/cm^2
- ✓ Thin column of vaporized metal when used in keyhole mode (focused)
- ✓ Narrow weld pool, thin HAZ
- ✓ Usually performed autogenously (without filler), but filler can be used on shallower welds
- ✓ Usually used with inert shielding gas (shroud or box) or vacuum
- ✓ Some materials reflect light, so photon absorption and thus, transfer efficiency varies on the material:
  - ✓ highly reflective materials (Al) ~ 10%
  - ✓ non-reflective materials (graphite) up to 90%
- ✓ Special coatings can be used to increase efficiency



Laser Beam Welding (LBW)

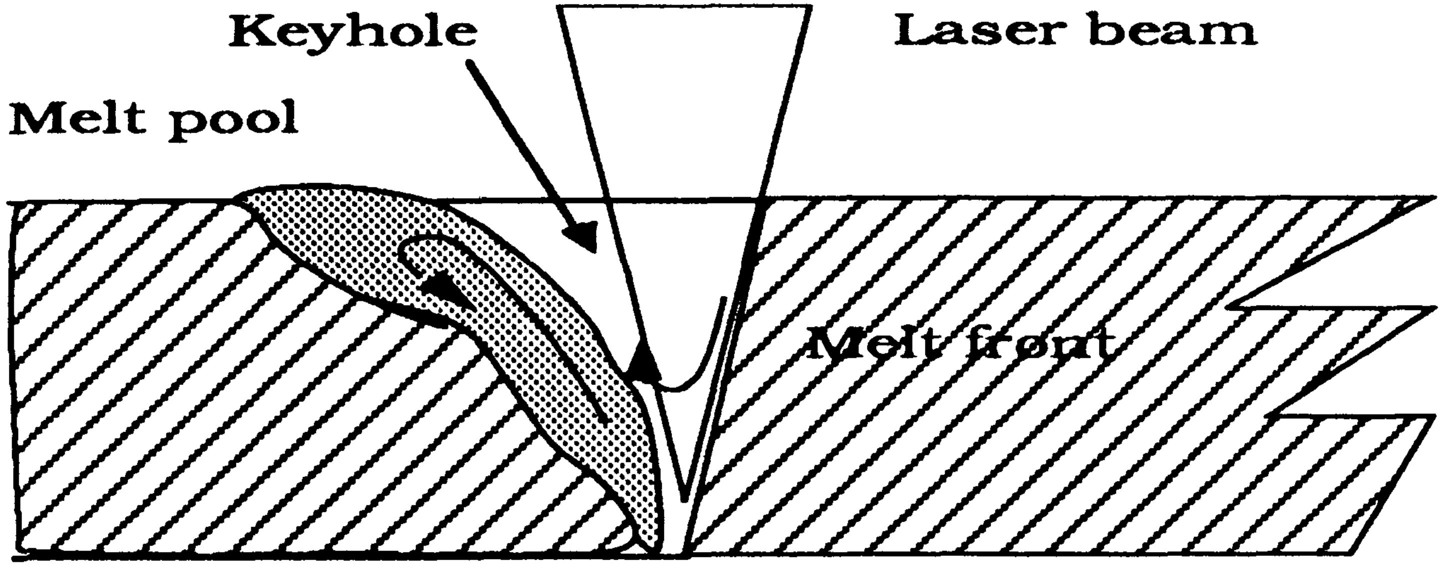
- ✓ Conduction mode welding is performed at low energy density, forming a weld nugget that is shallow and wide.
- ✓ Conduction/penetration mode occurs at medium energy density and shows more penetration than conduction mode.
- ✓ The penetration or keyhole mode welding is characterized by deep narrow welds.

- ✓ –In this mode, the laser light forms a filament of vaporized material known as a “keyhole” that extends into the material and provides a conduit for the laser light to be efficiently delivered into the material.

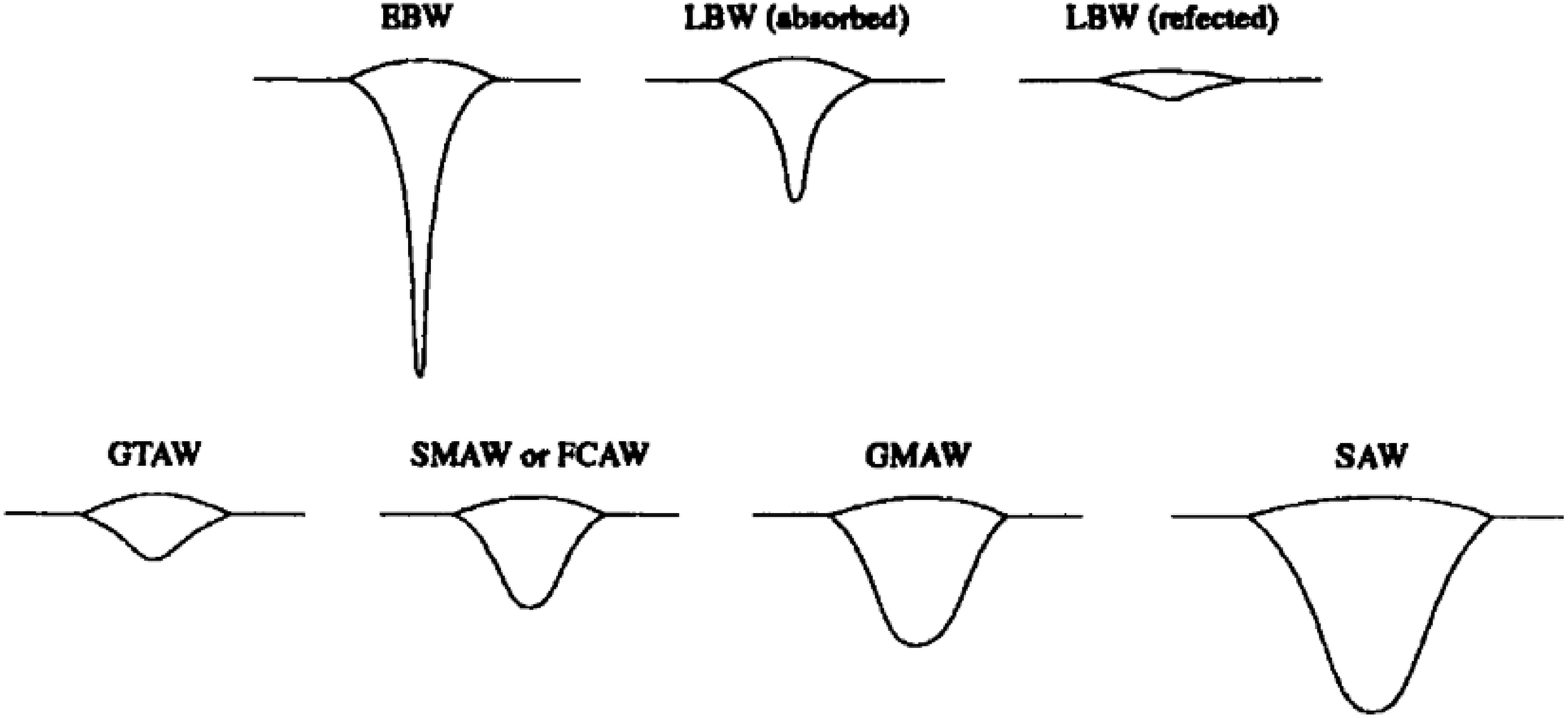
- ✓ –This direct delivery of energy into the material does not rely on conduction to achieve penetration, and so minimizes the heat into the material and reduces the heat-affected zone.

Laser Beam Welding (LBW)

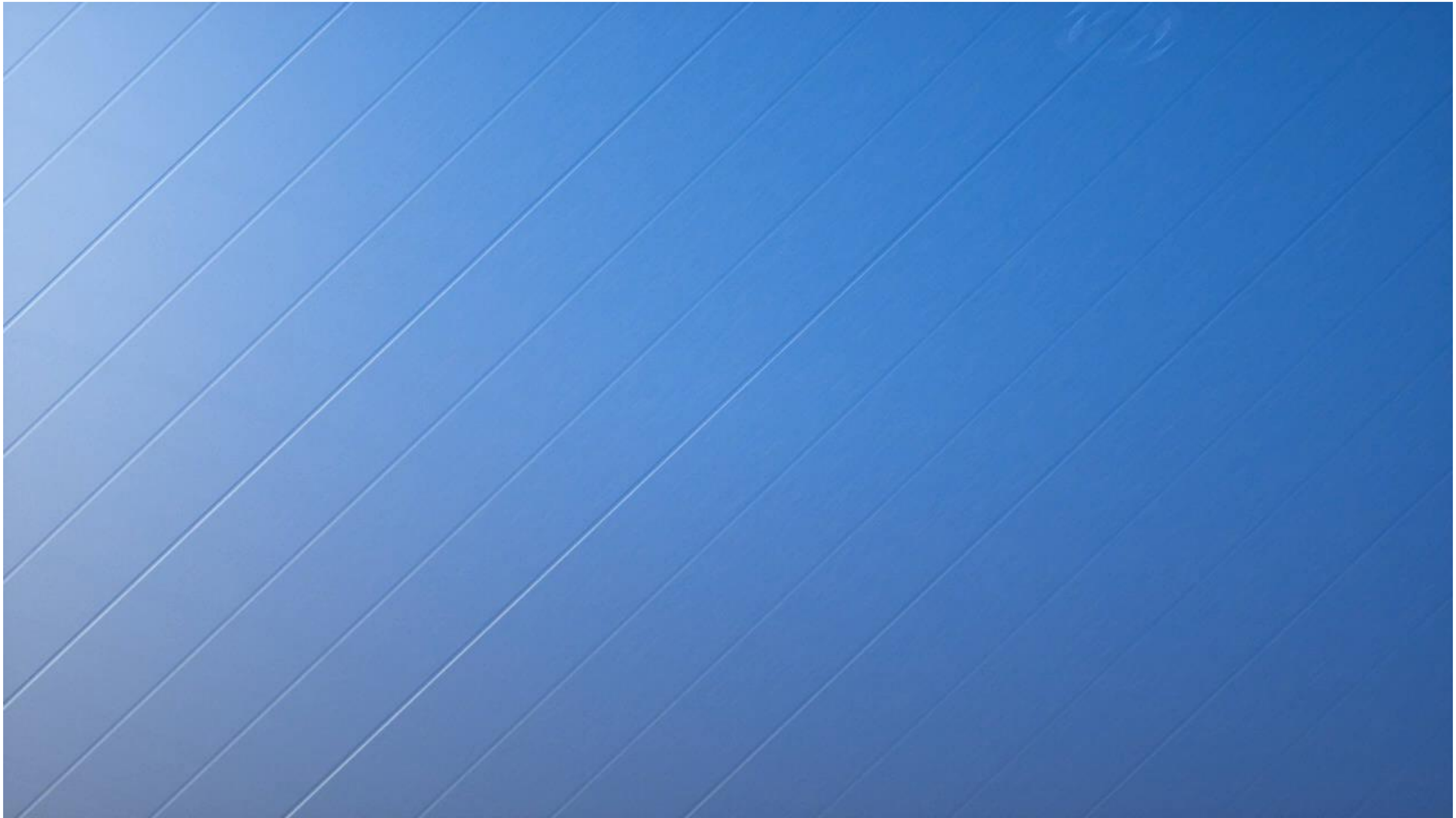
- ✓ At high power densities, all materials will evaporate if the energy can be absorbed. Thus, when welding in this way, a hole is usually formed by evaporation.
- ✓ This "hole" is then traversed through the material with the molten walls sealing up behind it.
- ✓ The result is what is known as a "keyhole weld. This is characterized by its parallel-sided fusion zone and narrow width.



Comparison of typical EB, LB, and conventional arc



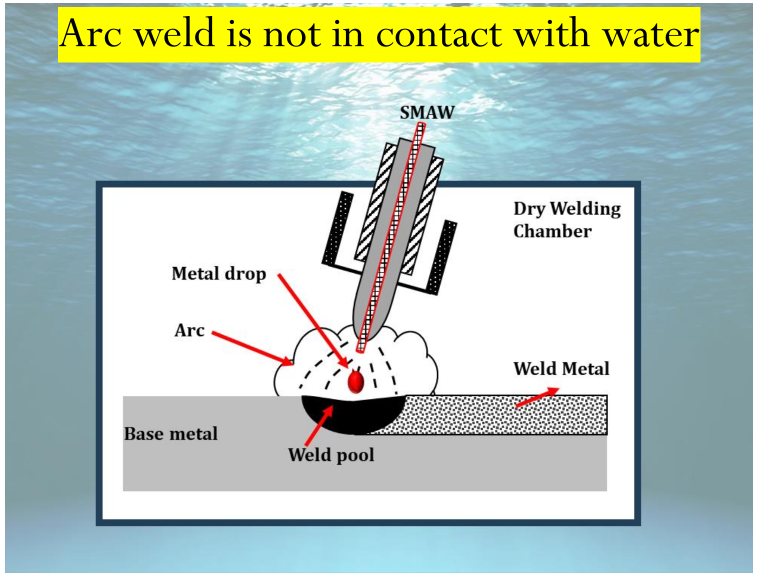
Additive manufacturing



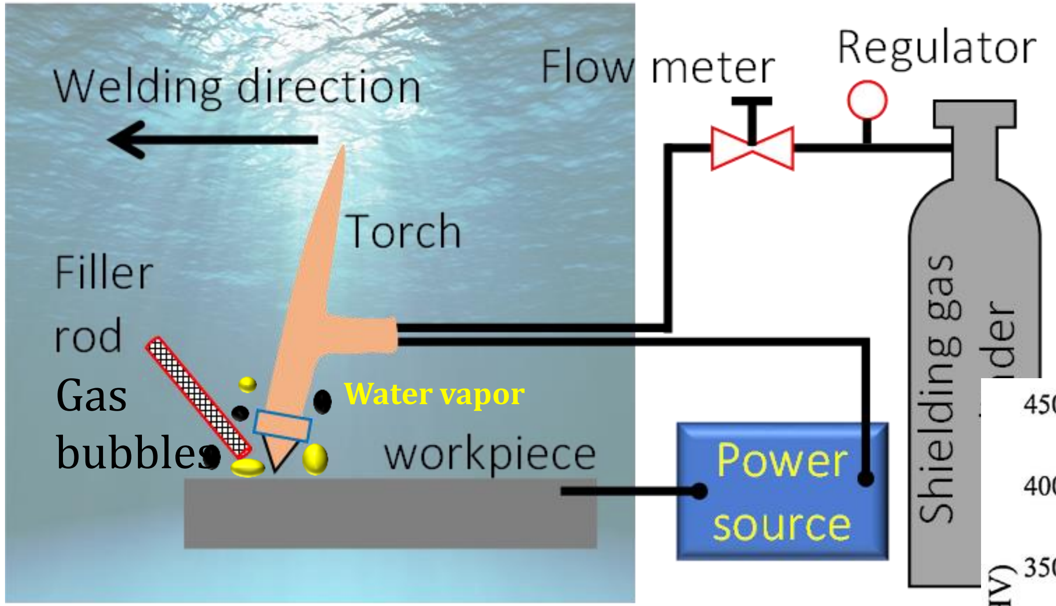
Underwater Welding

Type of underwater welding

Dry welding



Wet welding



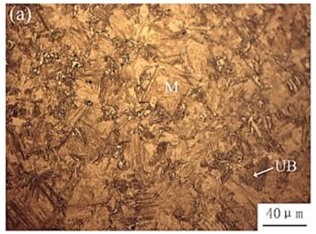
Applications

- Offshore structures and pipelines
- Repair nuclear reactors
- Offshore oil rigs
- Ship and submarines

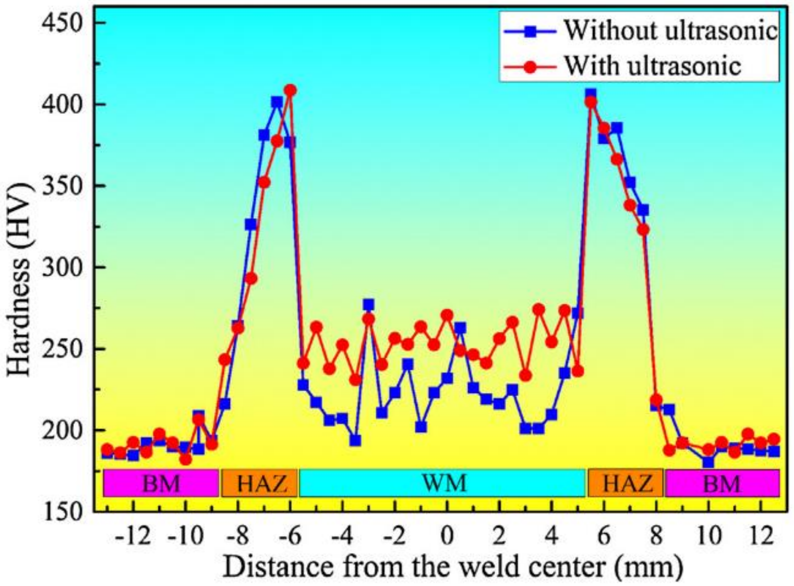
Problems in UWW

- High cooling rate: hardened structures HAZ
- High H_2 content
- Instability in the arc (arc blow)
- Cold cracking
- Salt also effects joints

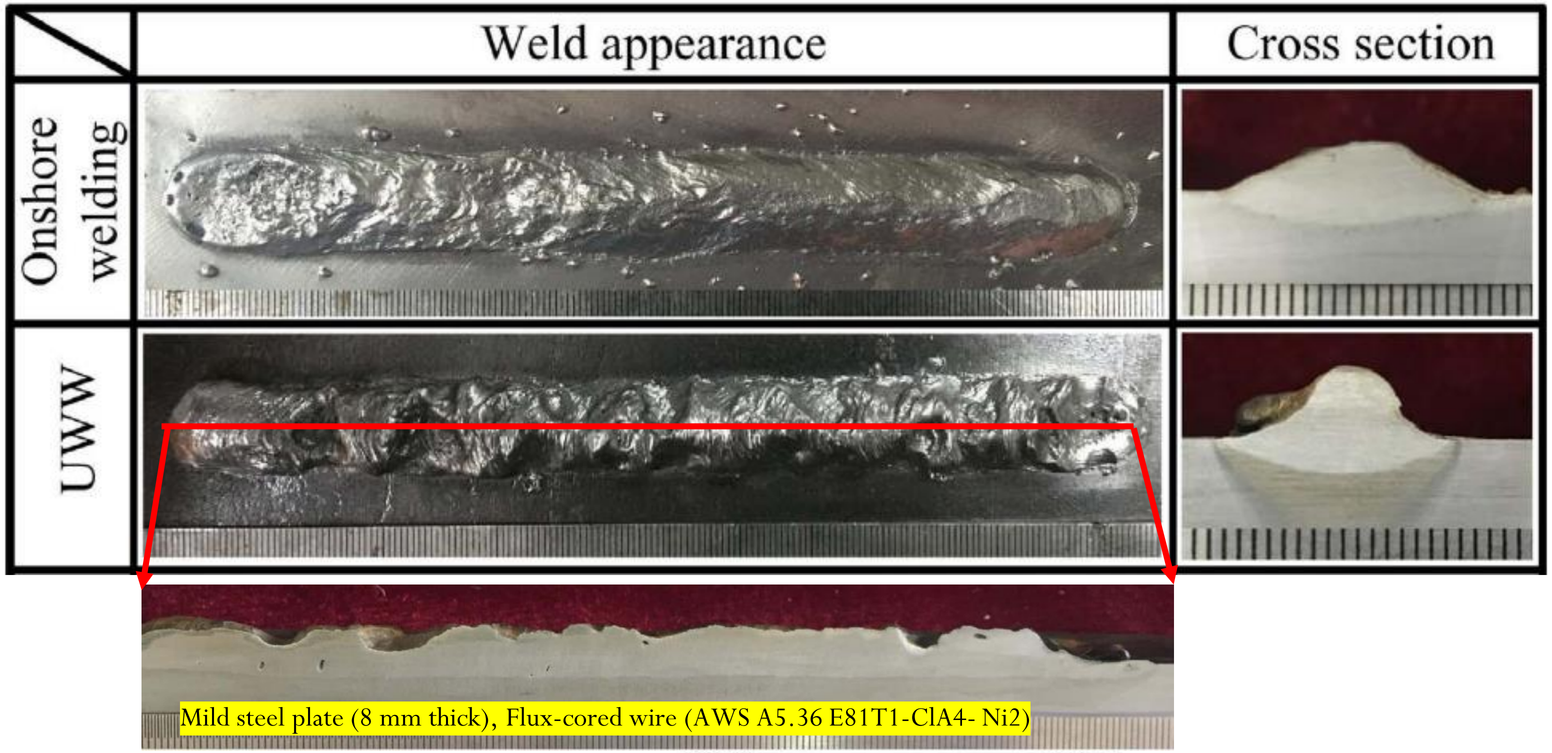
Process	Order of av. cooling rate (°C/s)
SMAW, GMAW,SAW and GTAW	10
Dry underwater welding	50
Wet underwater welding	>500

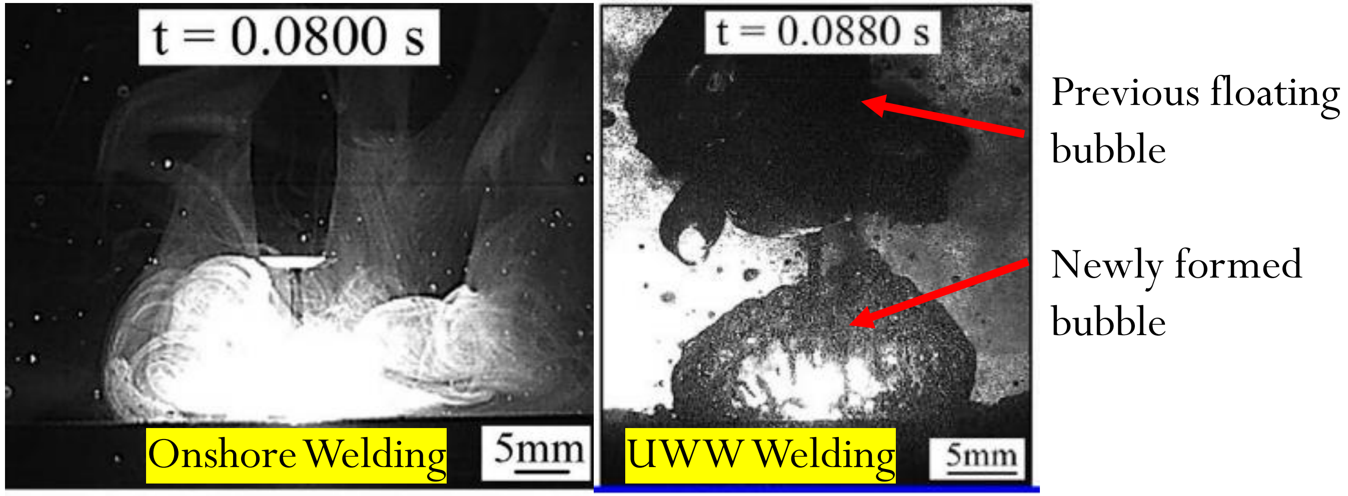


Wang et al., Journal of Materials Processing Technology, 2017



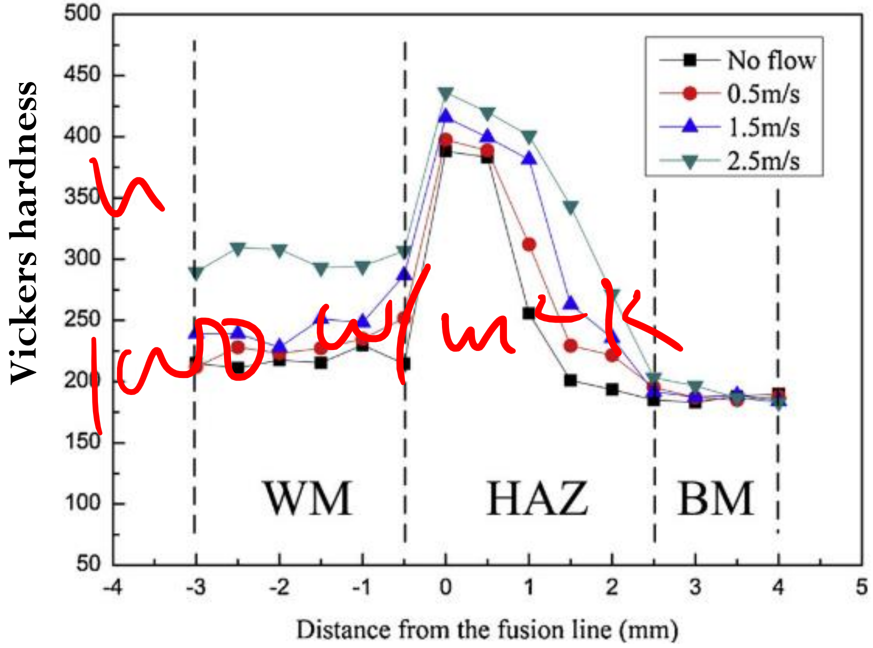
Underwater Welding



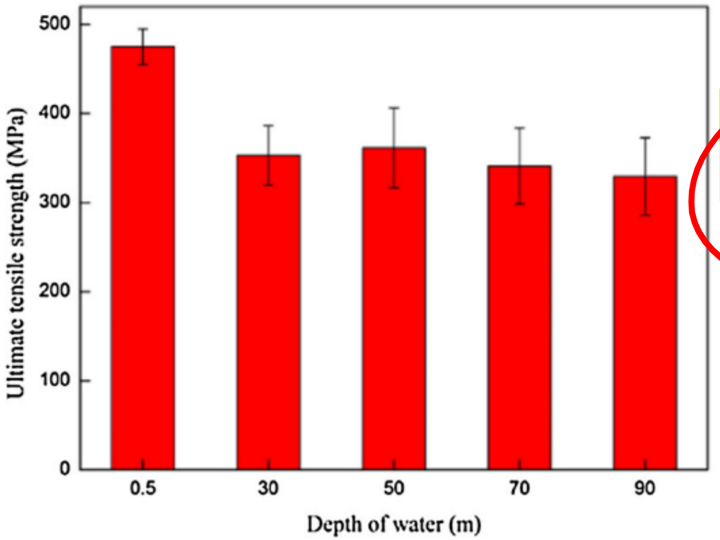


Wang et al., Journal of Materials Processing Technology, 2018

E40 steel joints



Chen et al., Journal of Materials Processing Technology, 2020



Marine Steel Plate EH40 (UTS 550MPa)

Chen et al., Journal of Materials Processing Technology, 2018