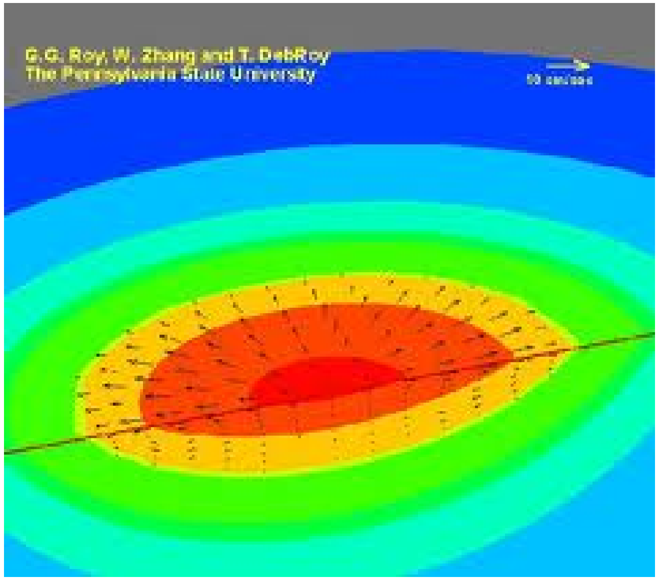
Welding Lectures: 8-10

Heat flow in welds

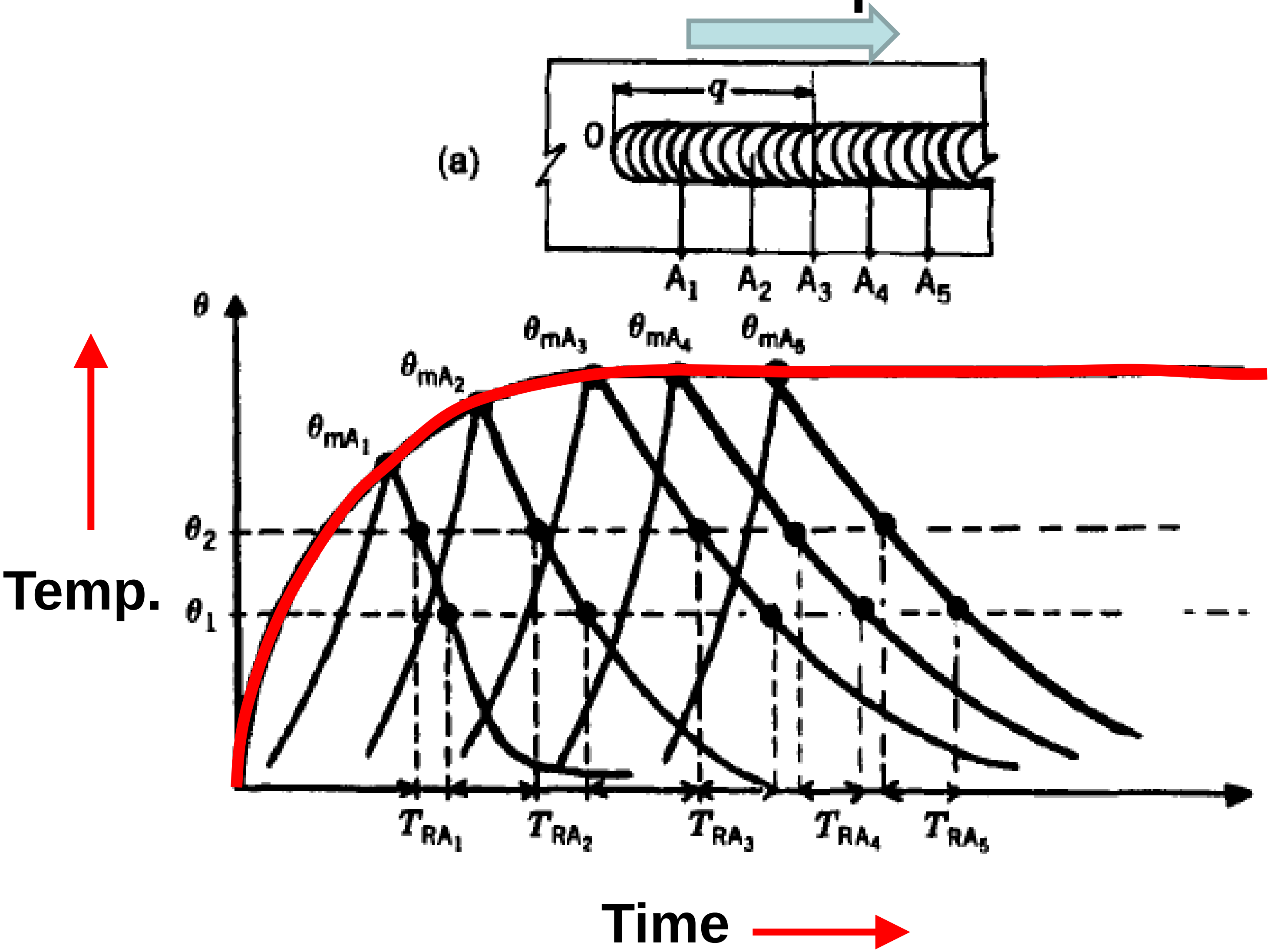


The welding thermal cycle

- Thermal excursion$\rightarrow$ Weld temp. ranges from the ambient temp. of the work environment to above the liquidus temp. (possibly to boiling point and above for some very high-energy-density processes)
- The severity of this excursion $\rightarrow$ in terms of the
  - temp. reached
  - time taken to reach them
  - the time remain at them

  completely determines the effects on structure (both microstructural for material changes and macrostructural for distortion)
- To quantify the thermal cycle mathematically, we need <u>temp. distribution</u> in <u>time</u> and <u>space</u> co-ordinates

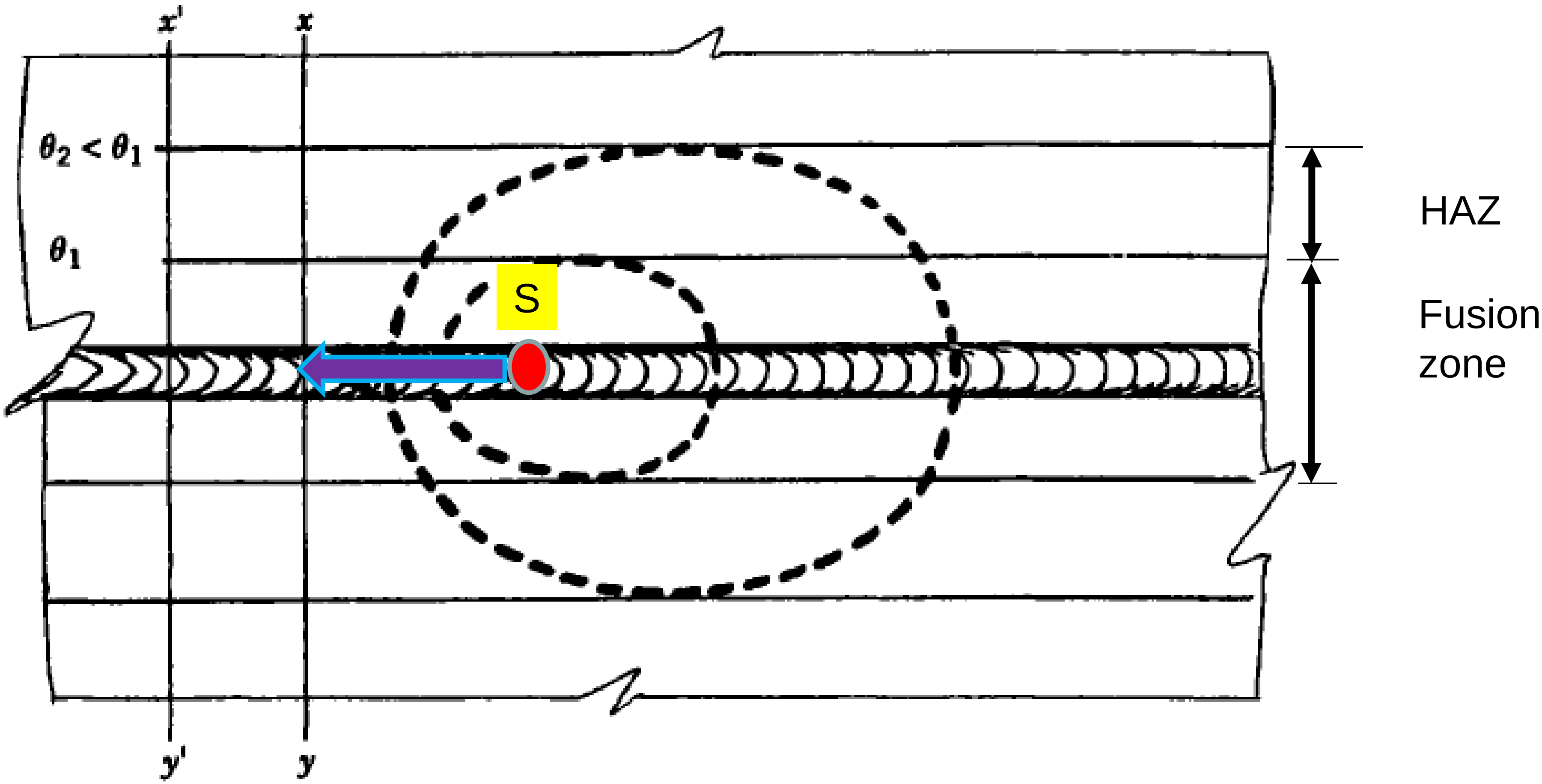
Thermal cycle characterization via thermocouples



Thermal cycle- quasi-steady state

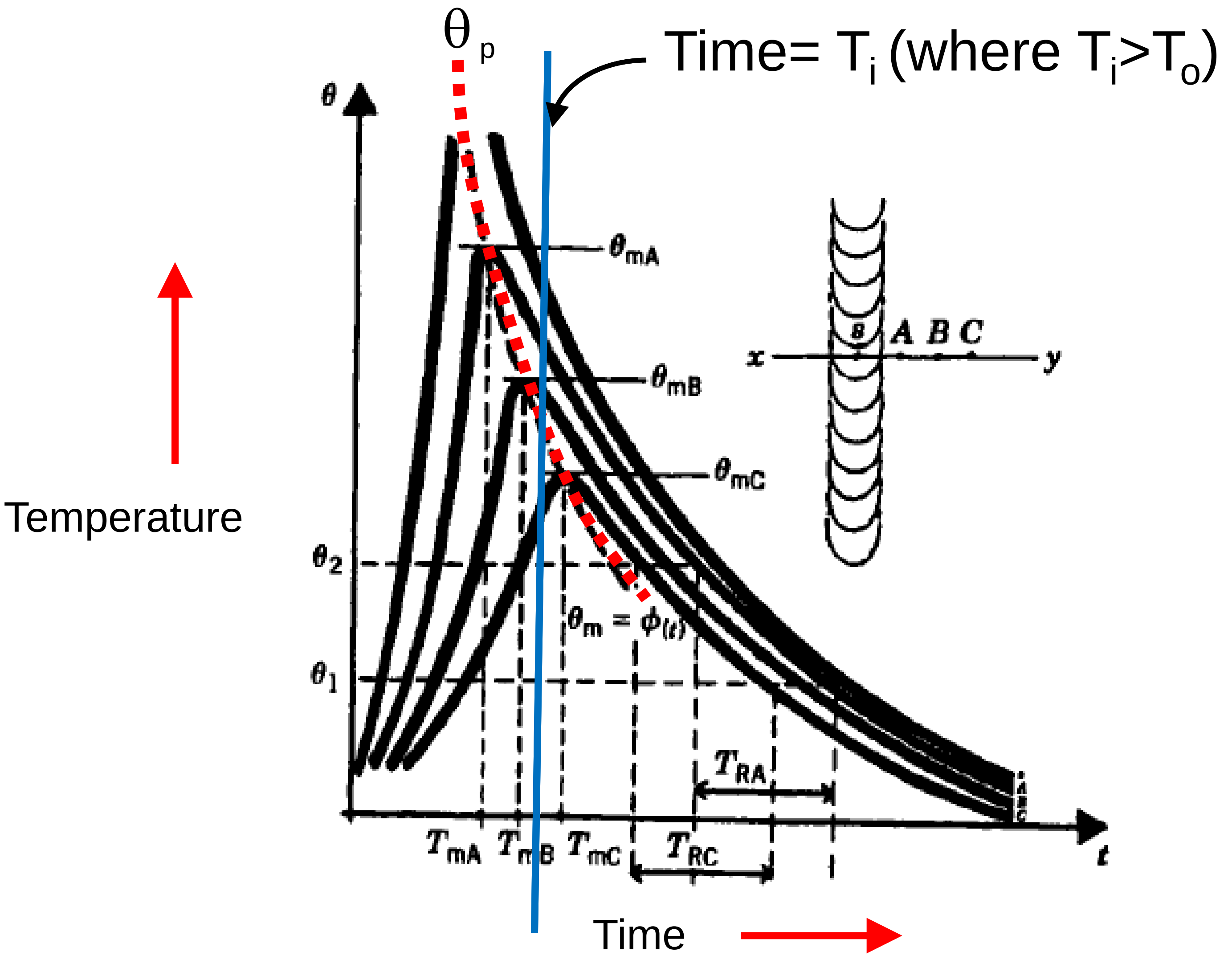
- Thermocouples $\rightarrow$ at various points along weld path
- Approach of the heat source $\rightarrow$ rapid rise in temperature to a peak $\rightarrow$ a very short hold at that peak $\rightarrow$ then a rapid drop in temperature once the source has passed by
- A short time after the heat from the source begins being deposited, $\rightarrow$ the peak temperature & rest of the thermal cycle, reaches a quasi-steady state
- Quasi-steady state $\rightarrow$ balance achieved between the rate of energy input and the rate of energy loss or dissipation
- Quasi-steady state $\rightarrow$ temperature isotherms surrounding a moving heat source remain steady and seem to move with the heat source (away from edges)

Thermal cycle- quasi-steady state



Temperature isotherms surrounding a moving heat source remain steady and seem to move with the heat source

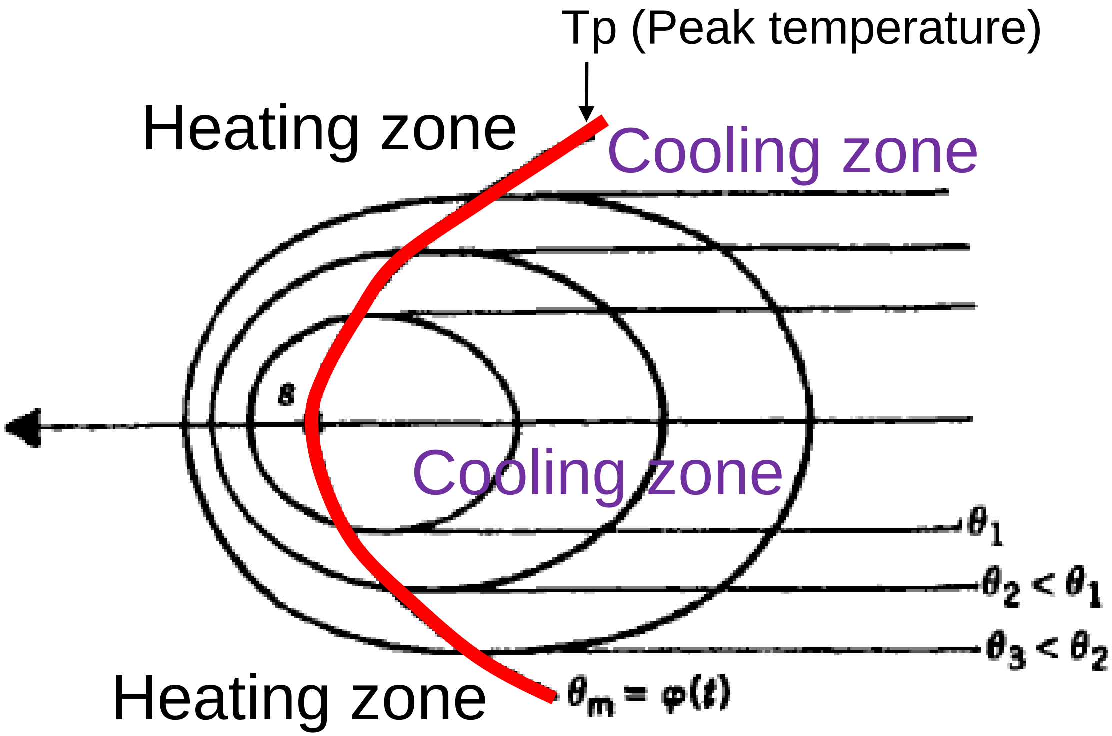
Time-Temperature curves



Time-Temperature curves

- The peak temp. decrease with increasing distance from the source, and more or less abruptly
- The maximum temperatures reached (T_{mA} T_{mB}, T_{mc}) decrease with distance from the weld line and occur at times (t_{mA}, t_{mB}, t_{mc}) that increase. This allows the peak temperature, T_p to be plotted as a function of time
- Peak temp. separates the heating portion of the welding thermal cycle from the cooling portion,
- At a time when points closest to a weld start cooling, the points farther away are still undergoing heating. This phenomenon explains
  - certain aspects of phase transformations that go on in the heat-affected zone,
  - **differential rates of thermal expansion/contraction** that lead to thermally induced stresses and, possibly, distortion

Spatial isotherms



- Peak temperature separates the heating zone & cooling zone

The generalized heat flow equation

- Temp. distribution$\rightarrow$ Controls microstructure, residual stresses and distortions, and chemical reactions (e.g., oxidation)
- The influencing parameters
  – the solidification rate of the weld metal,
  – the distribution of peak temperature in the HAZ
  – the cooling rates in the fusion and HAZ
  – the distribution of heat between the fusion zone and the heat-affected zone
- Requires mathematical formulation to quantify the influence of these parameters

The generalized heat flow equation

Heat supplied + Heat generated /Absorbed (chemical reaction) = Heat consumed (for temp rise, melting) + Heat transferred via conduction + Heat loss via convection & radiation

$$\rho C(T)\frac{dT}{dt} = \frac{d}{dx}\left[k(T)\frac{dT}{dx}\right] + \frac{d}{dy}\left[k(T)\frac{dT}{dy}\right] + \frac{d}{dz}\left[k(T)\frac{dT}{dz}\right]$$

$$- \rho C(T)\left(V_x\frac{dT}{dx} + V_y\frac{dT}{dy} + V_z\frac{dT}{dz}\right) + Q$$

The generalized heat flow equation

x = coordinate in the direction of welding (mm)

y = coordinate transverse to the welding direction (mm)

z = coordinate normal to weldment surface (mm)

T = temperature of the weldment, (K)

$k(T)$ = thermal conductivity of the material (J/mm $s^{-1}K^{-1}$) as a function of temperature

$\rho(T)$ = density of the material (g/mm^3) as a function of temp.

$C(T)$ = specific heat of the material (J/g^{-1} K^{-1}), as a function of temperature

V_x, V_y, and V_z = components of velocity

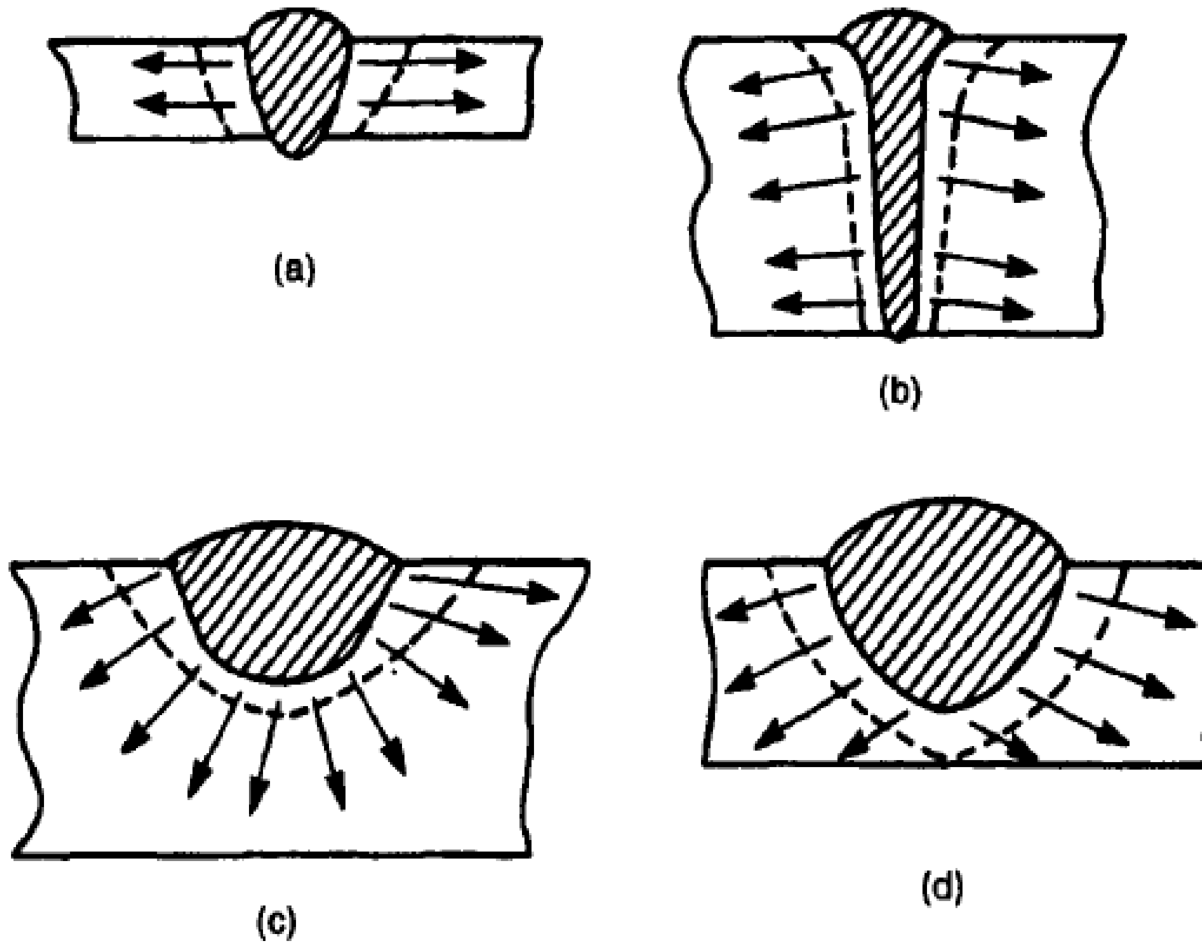
Q = rate of any internal heat generation, (W/mm^3)

The generalized heat flow equation

- This general equation needs to be solved for one, two, or three dimensions depends on
  - Weld geometry,
  - Whether the weld penetrates fully or partially
  - Parallel sided or tapered, and
  - Relative plate thickness
- **1-D solution** $\rightarrow$ <u>thin plate</u> or sheet with a <u>stationary source</u> or for welding under <u>steady state</u> (at constant speed and in uniform cross sections remote from edges) in very thin weldments
- **2-D solution** $\rightarrow$ thin weldments or in thicker weldments where the weld is full penetration and parallel-sided (as in EBW) to assess both longitudinal and transverse heat flow
- **3-D solution** $\rightarrow$ thick weldment in which the weld is partial penetration or non-parallel-sided (as is the case for most single or multipass welds made with an arc source)

Weld geometry and dimensionality of heat flow

(a) 2-D heat flow for full-penetration welds in thin plates or sheets;
(b) 2-D heat flow for full-penetration welds with parallel sides (e.g. EBW & LBW)
(c) 3-D heat flow for partial penetration welds in thick plate
(d) 3D, condition for near-full penetration welds (non parallel sides)



Rosenthal's Simplified Approach

- **Rosenthal's first critical assumption** $\rightarrow$ Energy input from the heat source was uniform and moved with a constant velocity v along the x-axis of a fixed rectangular coordinate system
- The net heat input to the weld under theseconditions is given by

$$H_{net} = \eta EI/v \quad (J/m)$$

where η is the the transfer efficiency of the process E and I are the welding voltage (in V) and current (in A), respectively, and v is the velocity of welding or travel speed (in m/s).

Rosenthal's Simplified Approach

Assumption 2 → Heat source is a point source, with all of the energy being deposited into the weld at a single point

- This assumption avoids complexities with density distribution of the energy from different sources and restricts heat flow analysis to the heat-affected zone, beyond the fusion zone or weld pool boundary.

Assumption 3 → The thermal properties (thermal conductivity, ***k,*** and product of the specific heat and density, ***Cp)*** of the material being welded are constants

Assumption 4 → Modify the coordinate system from a fixed system to a moving system

Rosenthal's solution

- Above equations can each be written in a simpler form, giving the time-temperature distribution around a weld when the position from the weld centerline is defined by a radial distance, r, where $\mathbf{r^2 = z^2 + y^2}$
- For the thin plate, the time-temperature distribution is

$$T - T_0 = \frac{q/v}{d(4\pi k\rho Ct)^{1/2}} e^{-r^2/4\alpha t}$$

and for the thick plate is

$$T - T_0 = \left(\frac{q/v}{2\pi kt}\right) e^{-r^2/4\alpha t}$$

Dimensionless Weld Depth Vs Dimensionless Operating Parameter

- Based on Rosenthal’s solution of the simplified three-dimensional heat flow equation, Christiansen et al. **(1965)** derived theoretical relationships between a weld bead’s cross-sectional geometry and the welding process operating conditions using dimensionless parameters.
- The theoretical relationship between the dimensionless weld width, ***D,*** and dimensionless operating parameter, ***n,*** is shown, where

Dimensionless Weld Depth Vs Operating Parameter n

$$D = \frac{dU}{2\alpha_s} \qquad n = \frac{QU}{4\pi\alpha_s^2 \rho C(T_m - T_0)}$$

d = depth of penetration of the weld,
U = welding speed (m/s),
α_s = thermal diffusivity (k/ρC) of the base material (as a solid),
Q = rate of heat input to the workpiece (J/s),
T_m = melting point of the base material (the workpiece), and
T_o = temperature of the workpiece at the start of welding.
For a symmetrical weld bead, the width of the weld bead w = 2d,
$\rightarrow$ Cross-sectional area of the weld bead can be determined

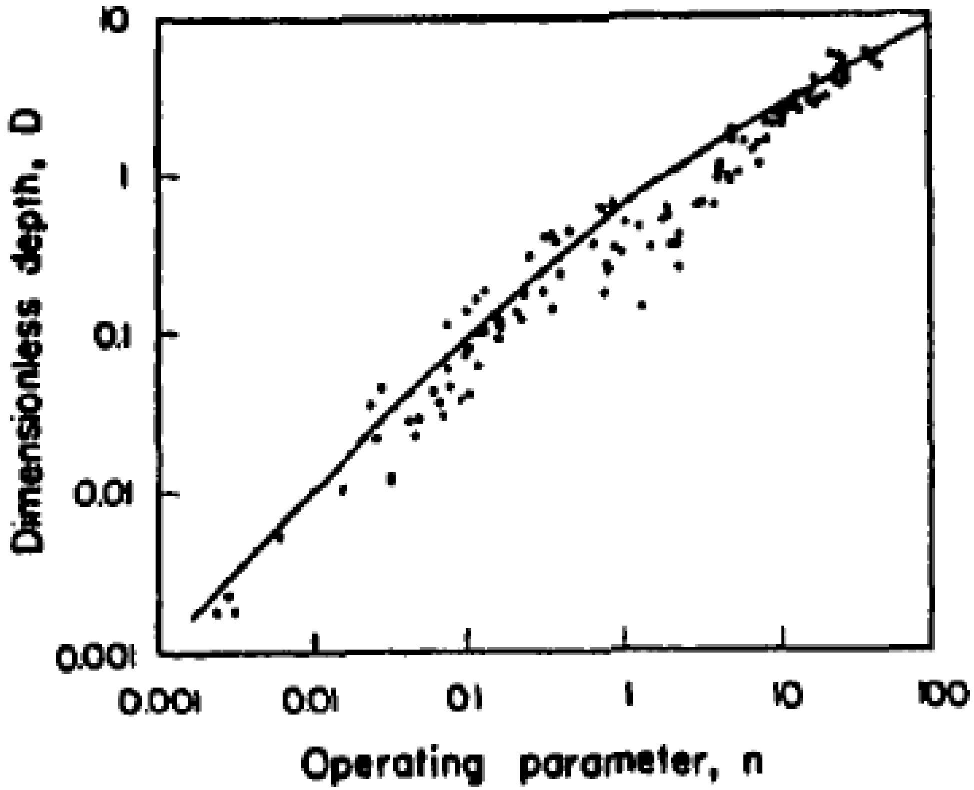
Can be applied to the heat-affected zone by simply substituting T_H for T_m where T_H is the temperature of some relevant phase transformation that could take place

Dimensionless weld depth (D) Vs process operating parameter n

Christiansen (1965)

$$D = \frac{dU}{2\alpha_s}$$

$$n = \frac{QU}{4\pi\alpha_s^2 \rho C(T_m - T_0)}$$

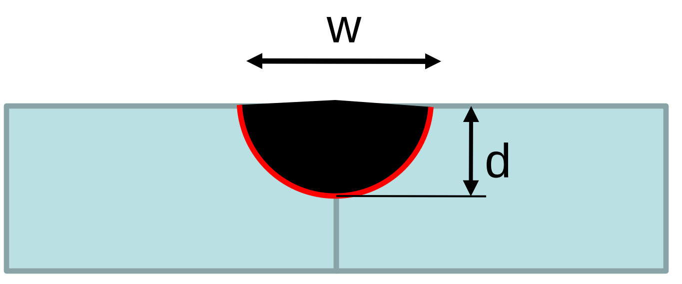


- Width of the weld bead can be determined (w = 2d)
- Width of heat-affected zone can be determined

Class Assignment -1

1) Find w and d for symmetrical weld bead as shown in figure.
2) Find the width of HAZ (phase transition temp = 730 C)

Material steel with T_m= 1510 C
E=20 V
I= 200 A
Welding speed (v or U) =5 mm/s
T_0= 25 C
Arc efficiency η=0.9
K=40 W/mK
ρC = 0.0044 J/mm^3. C
t=5 mm



Effect of welding parameters on heat distribution

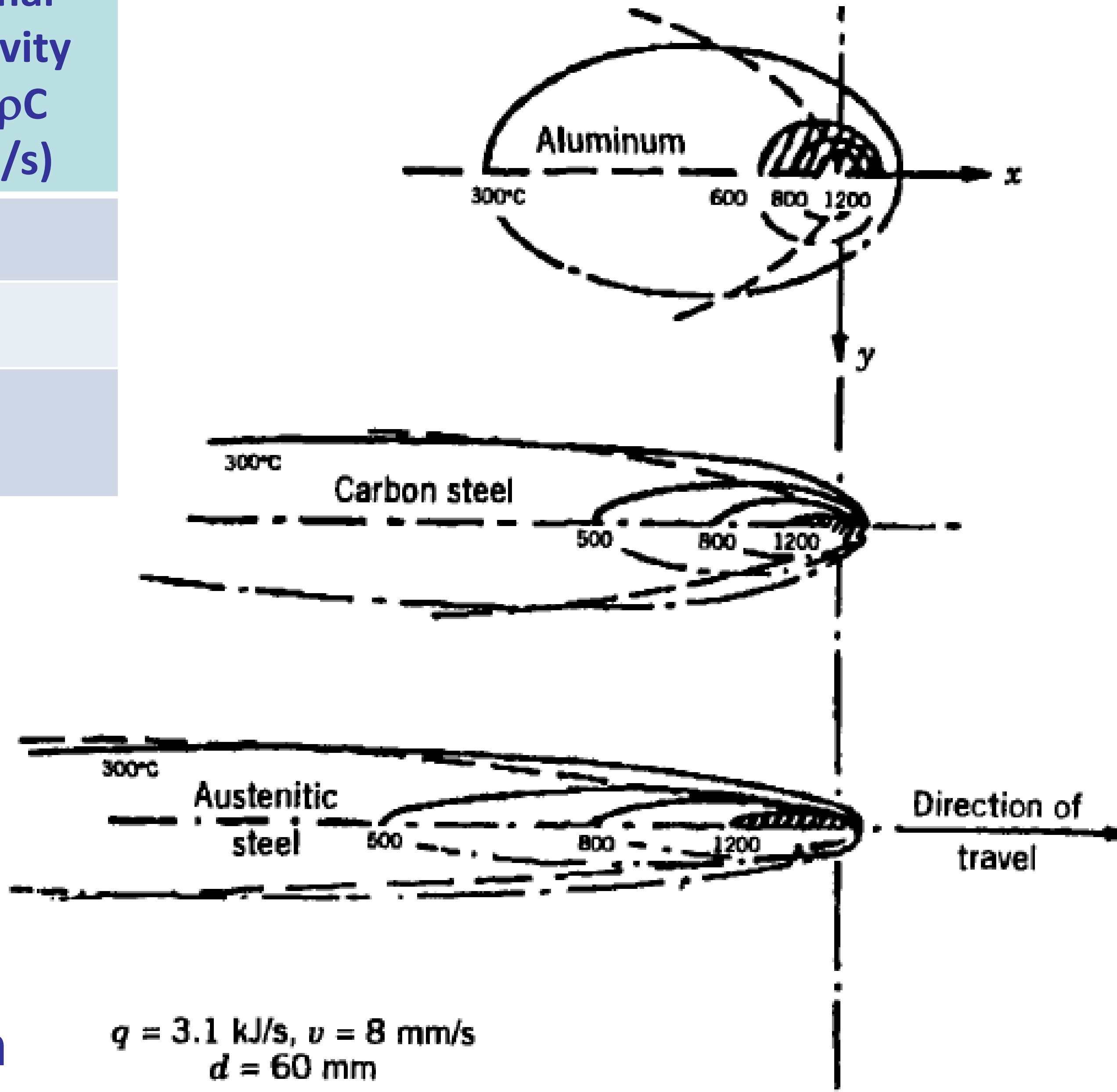
- The shape of the melt , size & heat distribution, is a function of
  1. Material properties (thermal conductivity, heat capacity, density)
  2. Welding speed, and
  3. Welding power/energy density
  4. Weldment plate thickness

Effect of thermal conductivity (and material property) on heat distribution

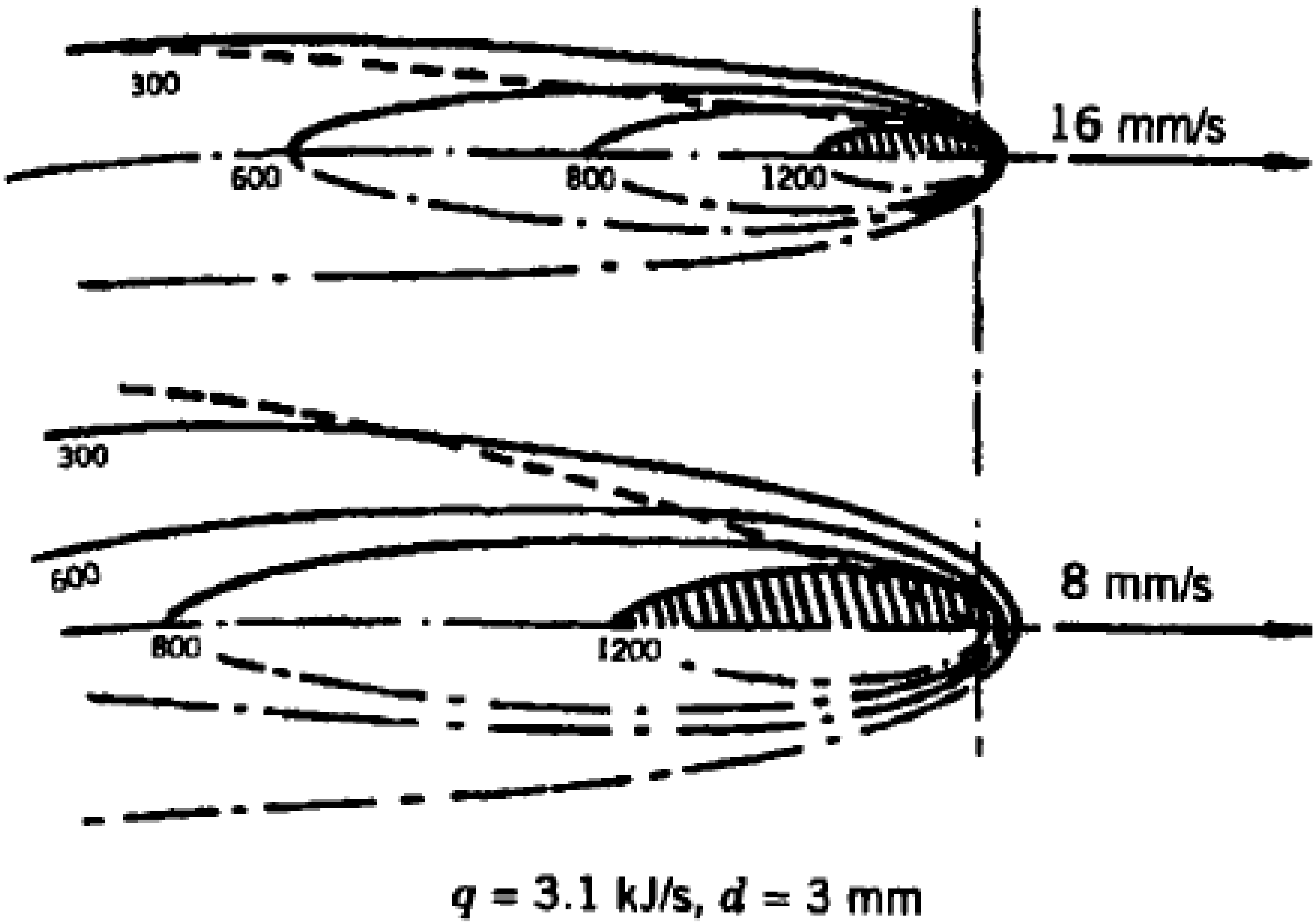
- Increasing thermal conductivity
  - tends to cause deposited heat to spread
  - Smaller welds for a given heat input and melting temperature
- For a given heat input, the lower the melting point, the larger the weld

Material	Thermal diffusivity $\alpha=k/\rho C$ (mm^2/s)
Aluminium	84
Carbon steel	12
Austenitic steel	4

Effect of thermal conductivity (and material property) on heat distribution



Effect of welding speed



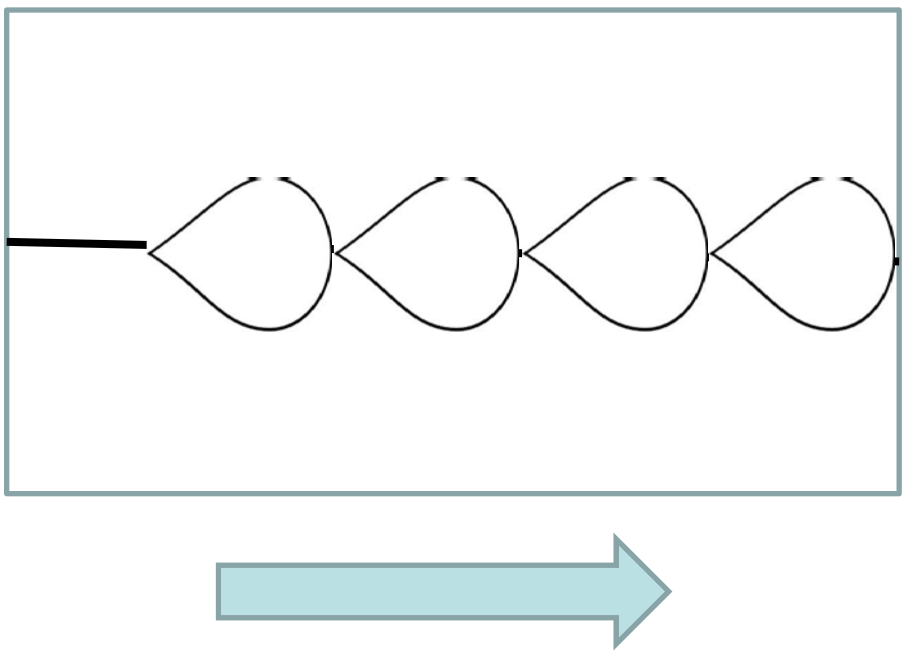
Effect of welding speed on Shape of Fusion/HAZ

Increasing velocity →

Velocity	0	Low	Medium	High	Very high
Plan view	Circle	elliptical	Elongated ellipse	Tear drop	Detached tear drop
3-D view	Hemi-spherical	Prolate spheroidal	Elongated prolate spheroidal	3D tear drop	3D tear drop

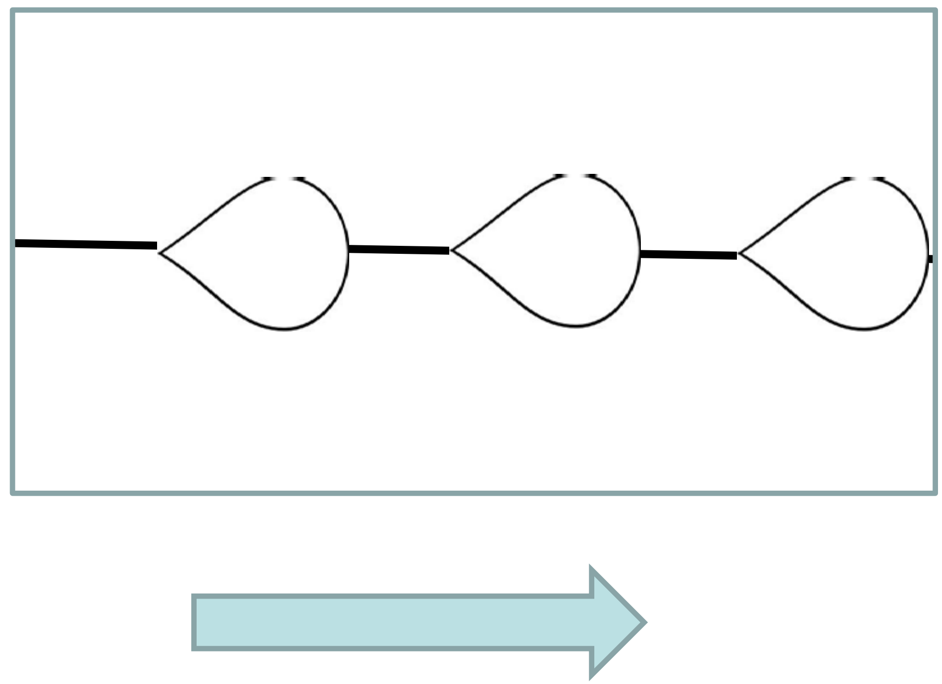
Tear drop formation at very high velocity

Continuous tear drops



Weld direction

Detached tear drops at very high velocity



Weld direction

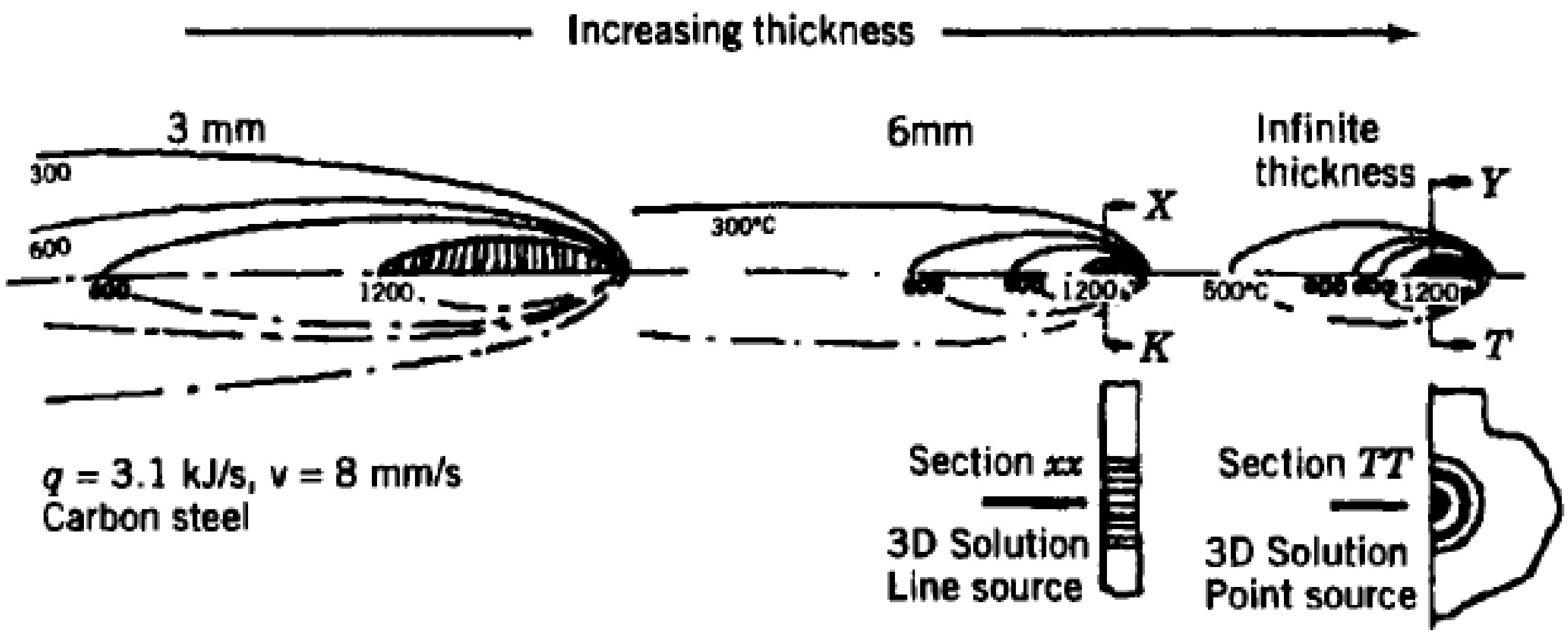
Effect of welding speed

- For a stationary (spot) weld, the shape, is round (plan view), and approximately hemispherical in 3-D
- Once the source is moved with constant velocity, the weld pool and surrounding HAZ become elongated to an elliptical shape (plan view), and prolate spheroidal in 3-D
- With increased velocity, these zones become more and more elliptical
- At some velocity (for each specific material), a <u>tear drop shape</u> forms, with a tail at the trailing end of the pool.

Effect of welding speed

- Increasing velocity $\rightarrow$ elongates the teardrop more and more, $\rightarrow$ narrows the fusion and heat-affected zone $\rightarrow$ overall melted volume constant
- Very high welding speeds $\rightarrow$ the tail of the teardrop weld pool detaches $\rightarrow$ isolate regions of molten metal $\rightarrow$ lead to <u>shrinkage-induced cracks</u> along the centerline of the weld

Efect of the thickness of a weldment



•Thick weldment → Small weld pool and heat-affected zone

Effect of energy density, Asymmetry

- Increased energy density → increases the efficiency of melting, → increases the amount of melting (especially in the depth direction) → decreases the heat-affected zone.
- Shape of weld pool & HAZ will be distorted by any asymmetry around the joint.
- Asymmetry might be the result of the relative thermal mass (e.g., thickness) of the joint elements as well as their relative thermal properties (Tm, k & C)

Simplified Equations for Approximating Welding Conditions

1) Peak Temperatures → Predicting metallurgical transformations (melting, austenitization, recrystallization of cold-worked material, etc.) at a point in the solid material near a weld requires some knowledge of the maximum temperature reached at that specific location.

→ For a single-pass, full-penetration butt weld in a sheet or a plate, the distribution of peak temperatures (Tp) in the base material adjacent to the weld is given by

$$\frac{1}{T_p - T_0} = \frac{(2\pi e)^{0.5} \rho C h y}{H_{net}} + \frac{1}{T_m - T_0}$$

Peak Temperature

$$\frac{1}{T_p - T_0} = \frac{(2\pi e)^{0.5} \rho C h y}{H_{net}} + \frac{1}{T_m - T_0}$$

T_o = initial temperature of the weldment (K)
e = base of natural logarithms = 2.718
ρ = density of the base material (g/mm3)
C = specific heat of the base material (J/g K- I)
h = thickness of the base material (mm)
y = 0 at the fusion zone boundary and where Tp = Tm
T_m = melting (or liquidus) temperature of the material being welded (K)
H_{net} = ηEI/v (J/m)

Width of the Heat-Affected Zone

- Peak temperature equation can be used to calculate the width of the HAZ.
- Define $T_p \rightarrow T_{re}$ or T_{au}
- The width of the HAZ is determined by the value of y that yields a T_p equal to the pertinent transformation temperature (recrystallization temperature, austenitizing temperature, etc.).
- Equation cannot be used to estimate the width of the fusion zone, since it becomes unsolvable when $T_p = T_m$
- (Remember the assumption in Rosenthal's solution of the generalized equation of heat flow, $\rightarrow$ Heat was deposited at a point, and there was no melted region, but just a HAZ)

Assignment 2

A single full penetration weld pass is made on steel using the following parameters.
T_m= 1510 C, E=20 V, I= 200 A, Welding speed (v or U) =5 mm/s, T_0= 25 C, Arc efficiency =0.9, $\rho C = 0.0044$ J/mm^3. C, t=5 mm, H_{net}= 720 J/mm

a) Calculate the peak temperatures at distances of 1.5 and 3.0 mm from the weld fusion boundary
b) Calculate the width of HAZ if the recrystallization temperature is 730° C
c) Find the influence on the width of HAZ if a preheated sample is used (Assume preheat temp =200° C)
d) Find the influence on the width of HAZ if the net energy is increased by 10%
e) Find the influence on the width of HAZ if the velocity is increased to 10 mm/s

Welding Lecture – 11-12

Solid state welding processes

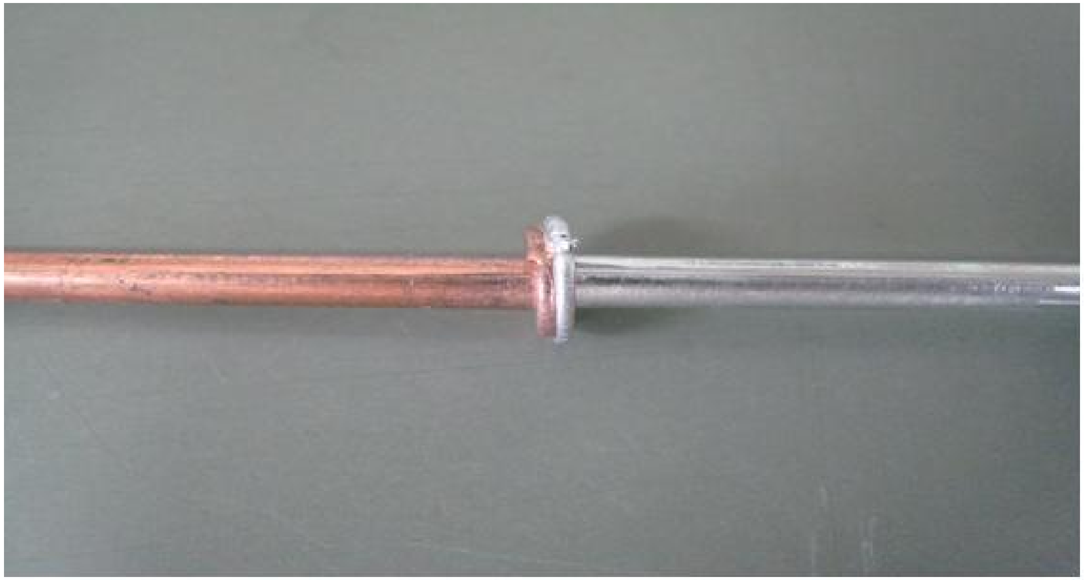
Solid state/Nonfusion welding

- Accomplish welding by bringing the atoms (or ions or molecules) to equilibrium spacing $\rightarrow$ through plastic deformation $\rightarrow$ application of pressure at temperatures below the melting point of the base material
- Without the addition of any filler
- Chemical bonds are formed and a weld is produced as a direct result of the continuity obtained, $\rightarrow$ always with the added assistance of solid-state diffusion

Solid state/Nonfusion welding

1. **<u>Pressure Welding</u>** → By pressure and gross deformation
2. **<u>Friction welding</u>** → By friction and microscopic deformation
3. **<u>Diffusion welding</u>** → By diffusion, without or with some deformation
4. **<u>Deposition welding</u>** → Solid-state deposition welding

Pressure Welding→Cold welding



- Pressure is used at room temperature to produce coalescence of metals with substantial plastic deformation → No heat
- The faying surfaces must be exceptionally clean
- Cleaning is usually done by degreasing and wire brushing immediately before joining

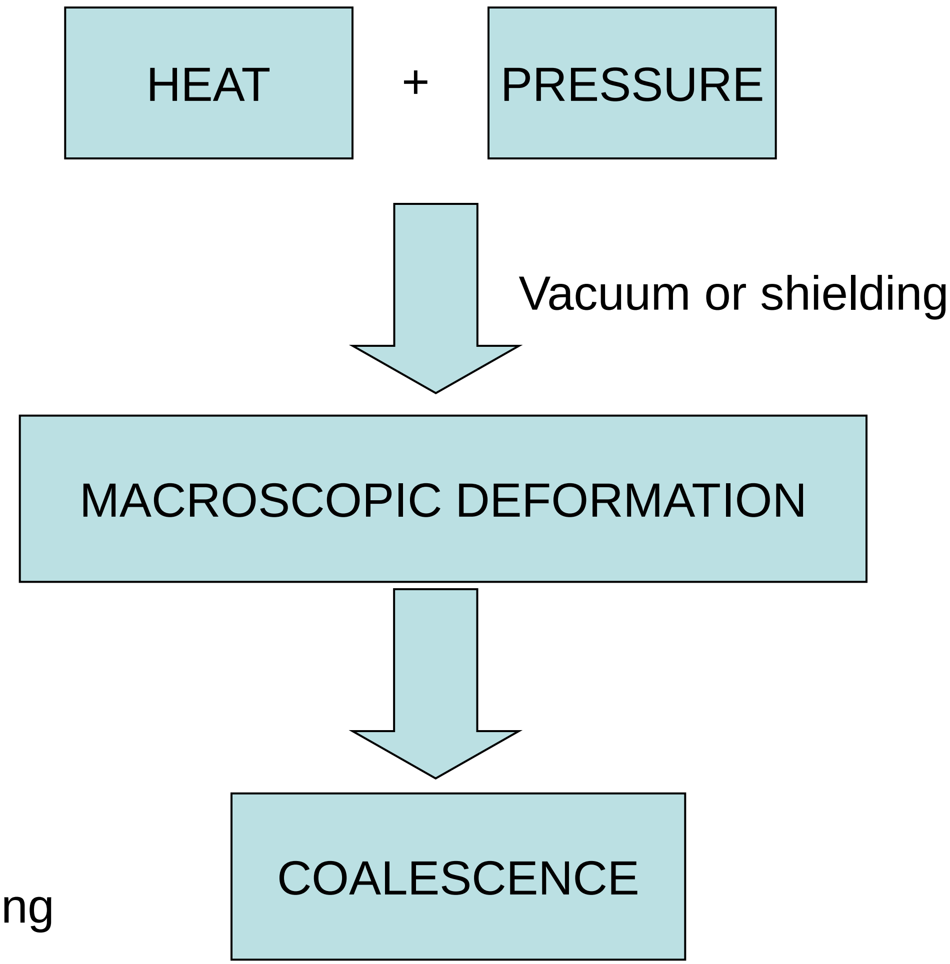
Pressure Welding →Cold welding

- At least one of the metals to be joined must be highly ductile and not exhibit extreme work hardening
- FCC metals and alloys are best suited for CW. Example- Al, Cu, and Pb
- To a lesser degree, Ni and soft alloys of these metals such as brasses, bronzes, babbitt metals (Sn, Cu, Sb, Pb), and pewter (Sn, Cu, Sb, Bi)
- Precious metals, Au, Ag, Pd, and Pt, are also ideally suited to cold welding, as they are face-centered cubic (soft) and are almost free of oxides

Pressure Welding $\rightarrow$ Cold welding

- Ideal for joining of dissimilar metals $\rightarrow$ no intermixing of the base metals is required
- Allows inherent chemical incompatibilities that make fusion welding difficult to be overcome
- E.g. $\rightarrow$ Cold welding of relatively pure *Al* to relatively pure *Cu* $\rightarrow$ Electrical connections
- Formation of brittle intermetallics (e.g., Al,Cu) $\rightarrow$ either during postweld heat treatment or in service, (resistance heating in the electrical connector)

Pressure Welding→Hot Pressure Welding

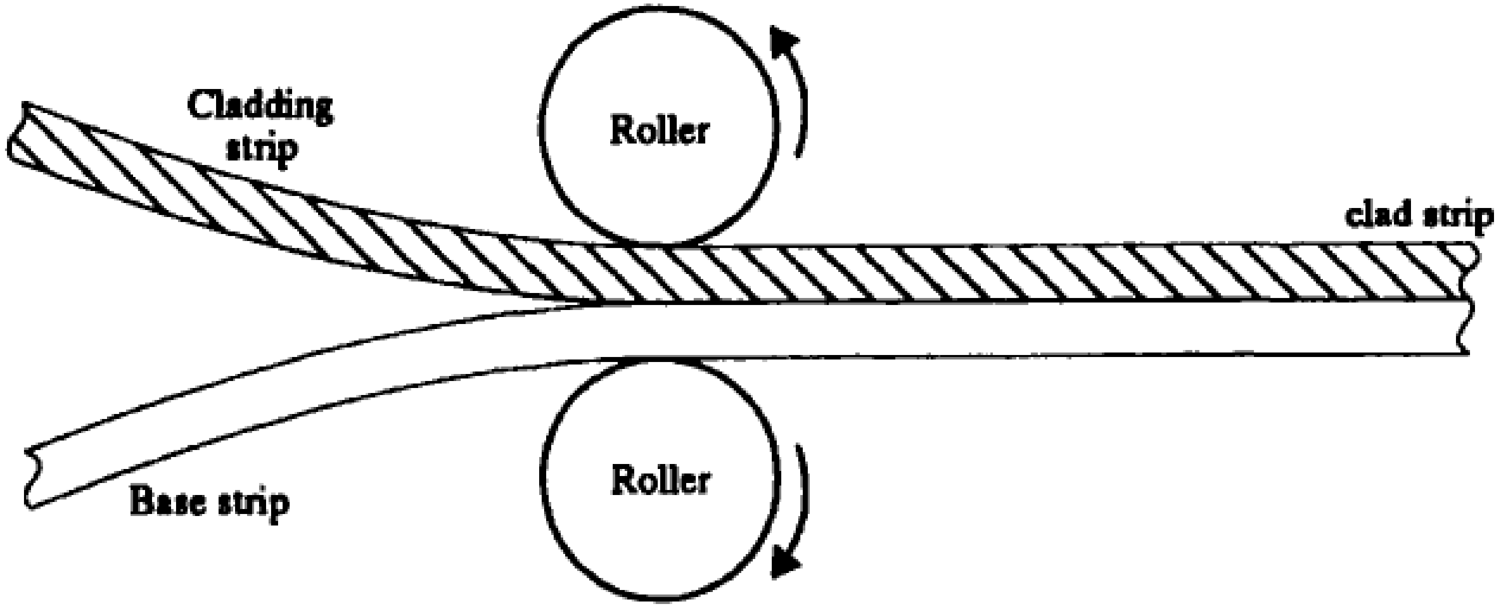


Examples:
1) Pressure gas welding
2) Forge welding

Pressure Welding→ Forge welding (FOW)

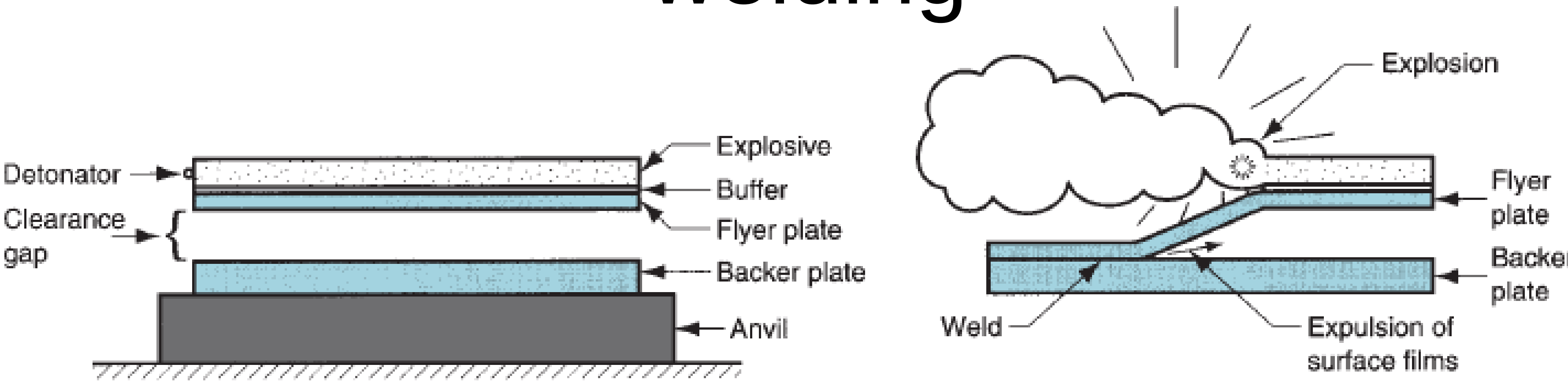
- Earliest form of welding → still used today by blacksmiths
- Produces the weld by heating work pieces to hot working temperatures and applying blows sufficient to cause deformation at the faying surfaces
- Low-carbon steels (most commonly forge-welded metal), high-carbon steel

Pressure Welding→Roll Welding



- Pressure applied by rollers → Performed hot or cold
- Applications → cladding stainless steel to mild or low alloy steel for corrosion resistance
- Making bimetallic strips
- Producing ‘‘sandwich’’ coins for the U.S. mint

Pressure Welding→Explosion welding



- Coalescence of two metallic surfaces is caused by the energy of a detonated explosive
- Commonly used to bond two <u>dissimilar metals</u>
- E.g. → To clad one metal on top of a base metal over <u>large areas</u>

Pressure Welding→Explosion welding: Applications

- Applications include production of corrosion-resistant sheet and making processing equipment in the chemical and petroleum industries
- E.g. Commercially pure titanium clad to mild steel
- Often performed under water to enhance the shock wave to move and deform material

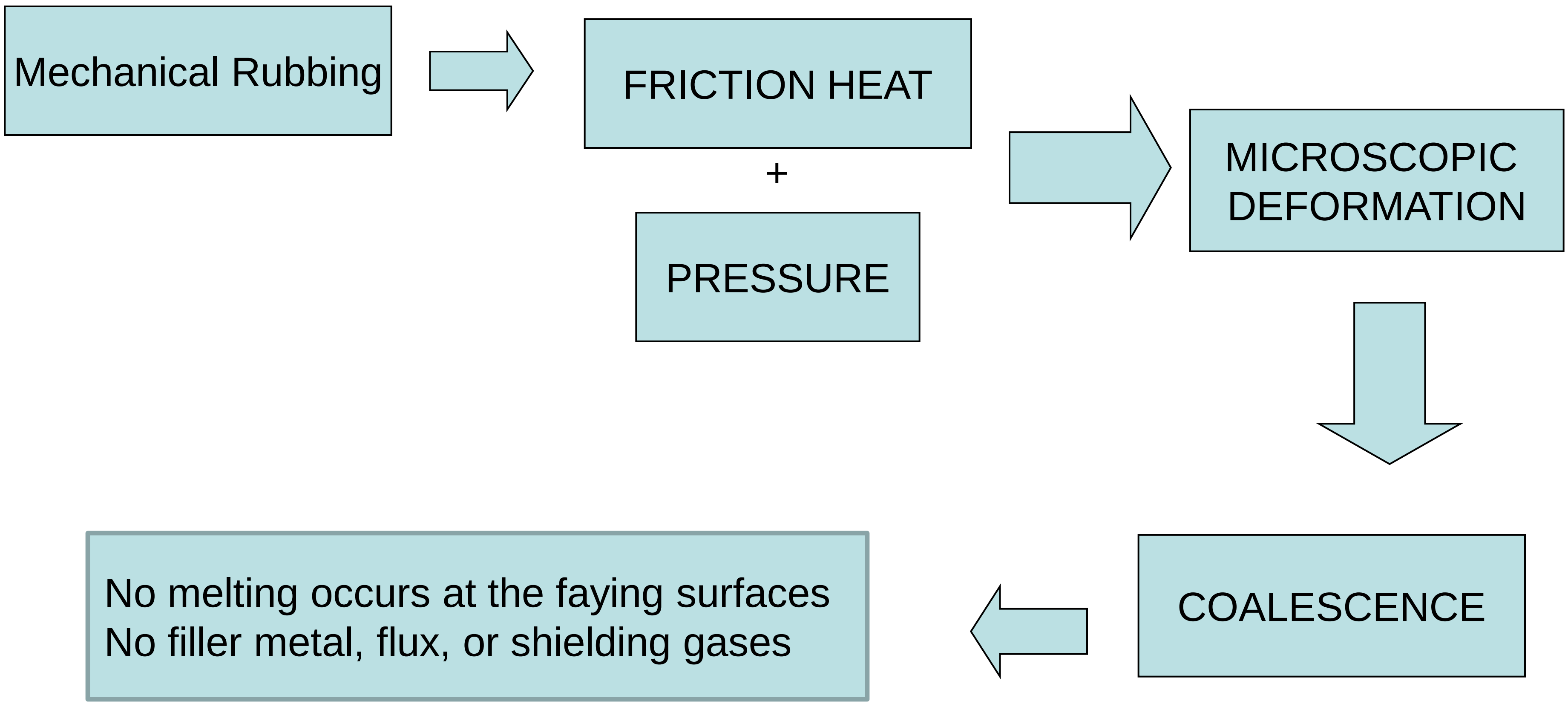
Compatible materials for Explosion welding

	ZIRCONIUM	MAGNESIUM	COBALT ALLOYS	PLATINUM	GOLD	SILVER	COLUMBIUM	TANTALUM	TITANIUM	NICKEL ALLOYS	COPPER ALLOYS	ALUMINUM ALLOYS	STAINLESS STEELS	ALLOY STEELS	CARBON STEELS
CARBON STEELS	●	●			●	●	●	●	●	●	●	●	●	●	●
ALLOY STEELS	●	●	●					●	●	●	●	●	●	●	
STAINLESS STEELS			●		●	●	●	●	●	●	●	●	●		
ALUMINUM ALLOYS		●				●	●	●	●	●	●	●			
COPPER ALLOYS					●	●	●	●	●	●	●				
NICKEL ALLOYS		●		●	●			●	●	●					
TITANIUM	●	●				●	●	●	●						
TANTALUM					●		●	●							
COLUMBIUM				●			●								
SILVER						●									
GOLD															
PLATINUM				●											
COBALT ALLOYS															
MAGNESIUM		●													
ZIRCONIUM	●														

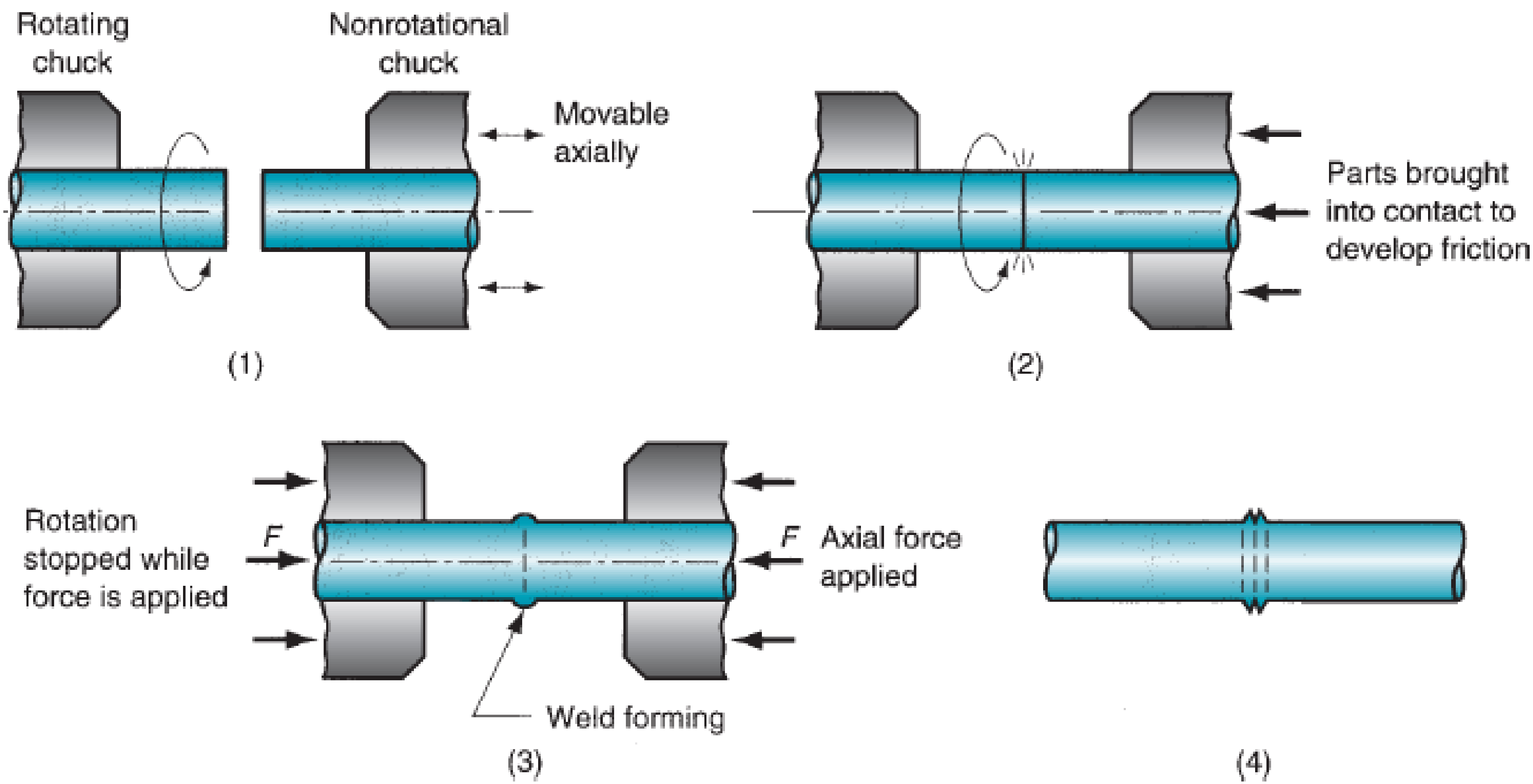
2.1 Friction welding (FRW)

- Solid state welding $\rightarrow$ Coalescence is achieved by frictional heat combined with pressure
- Friction is induced by mechanical rubbing between two surfaces $\rightarrow$ usually by rotation of one part relative to the other $\rightarrow$ raises the temperature at the joint interface to the hot working range $\rightarrow$ Parts are driven toward each other with sufficient force to form a metallurgical bond

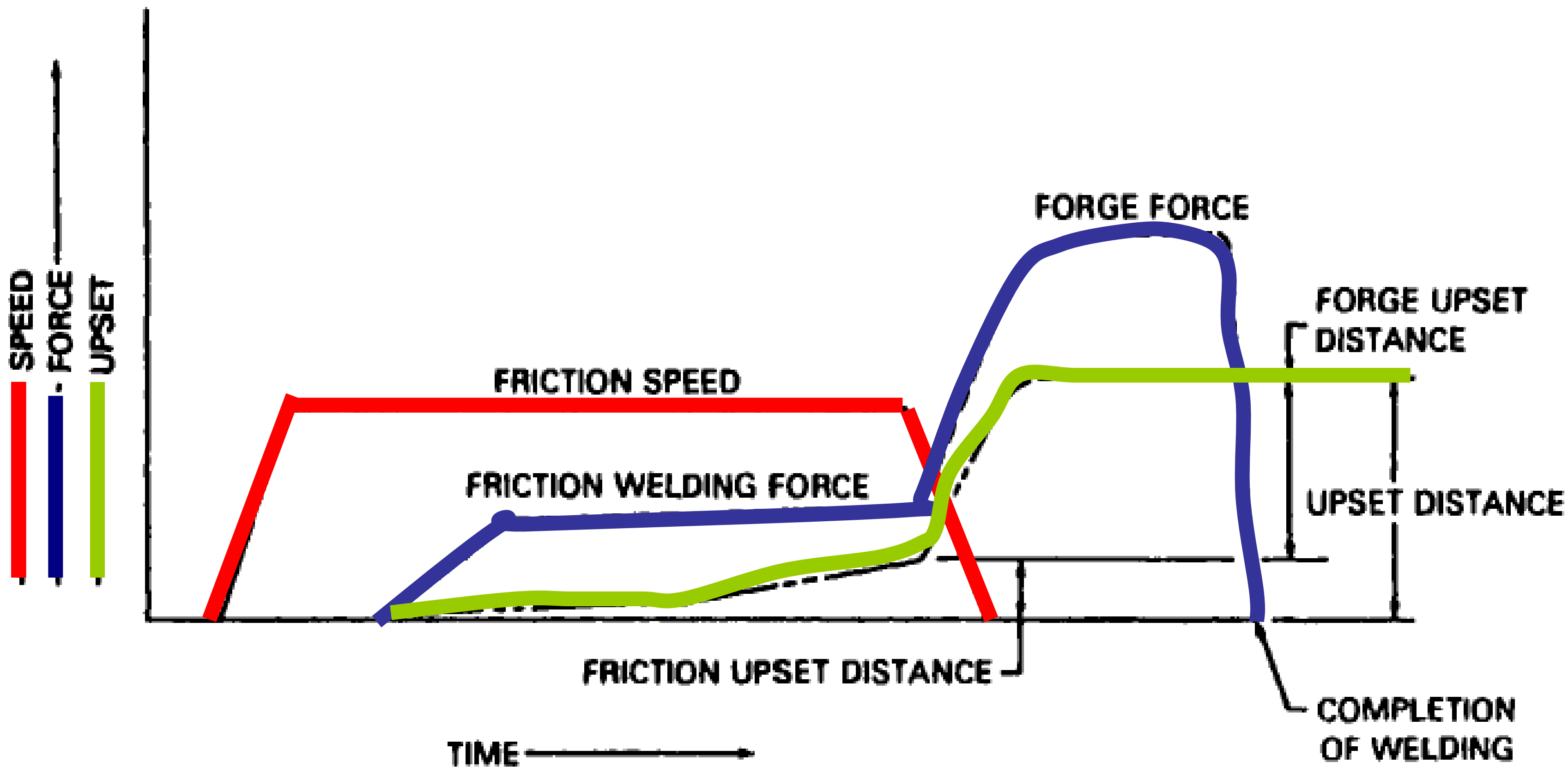
2.1 Friction welding (FRW)



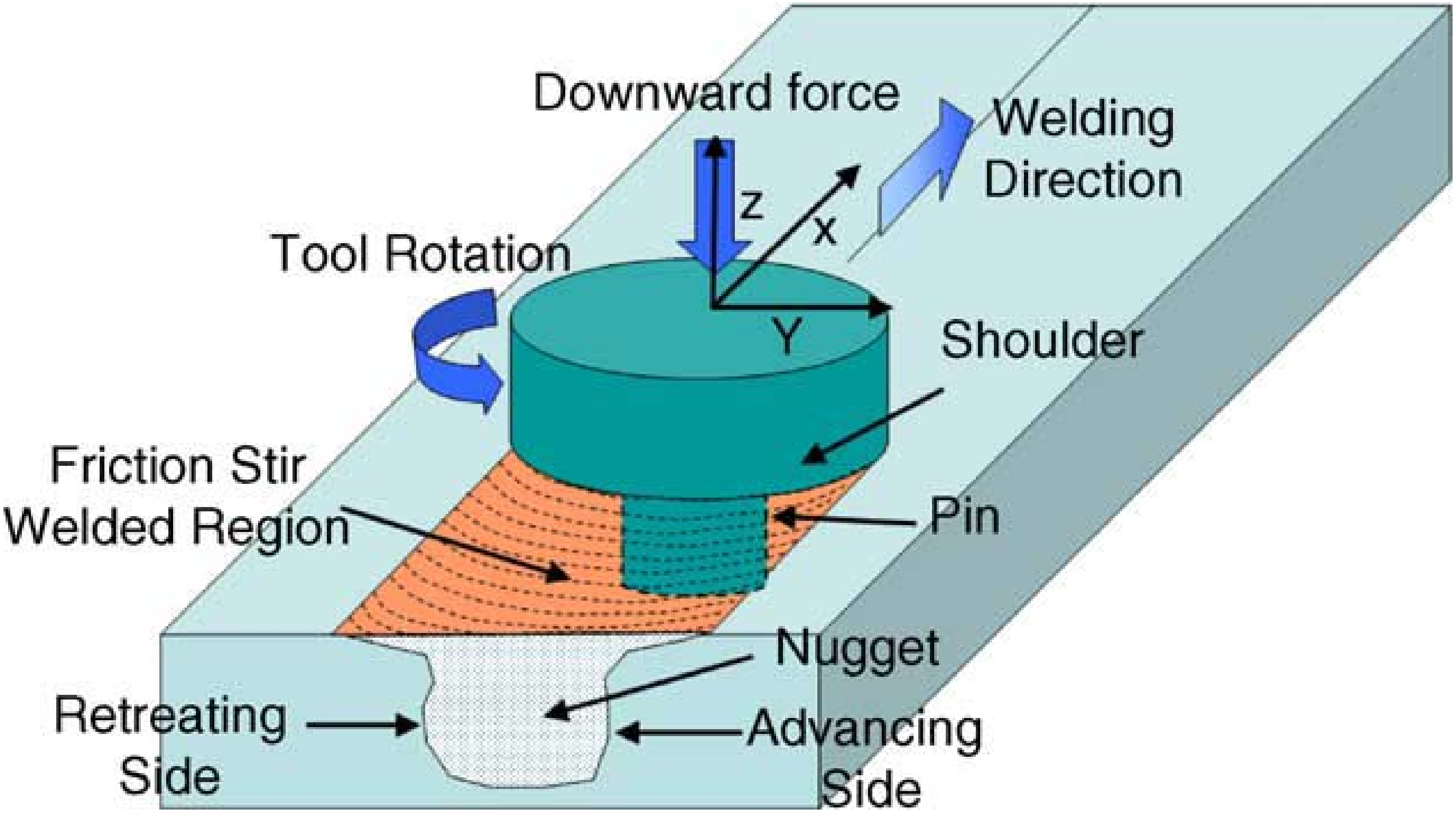
2.1 Friction welding (FRW)



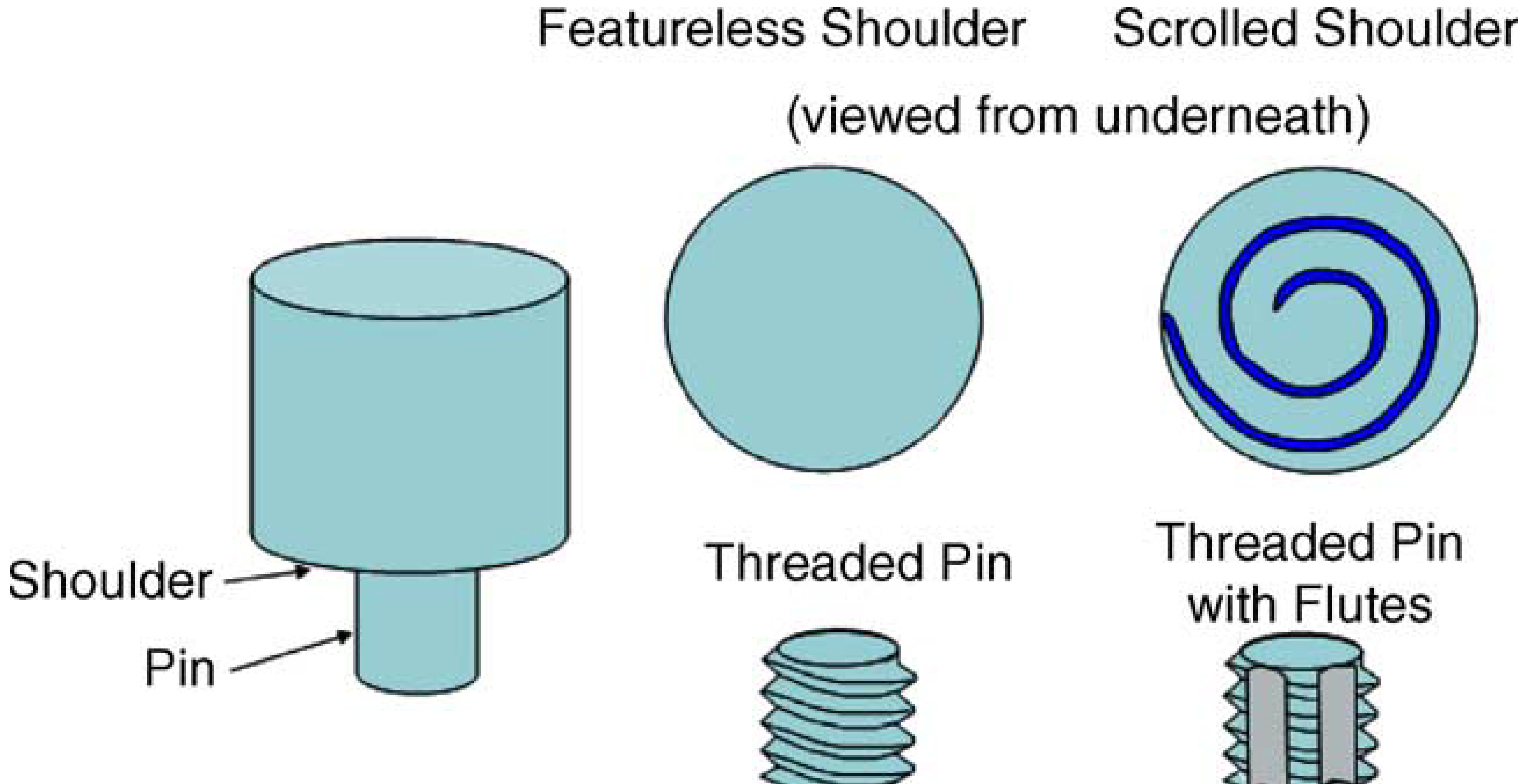
Drive parameter characteristics in FRW



2.2 Friction stir welding (FSW),

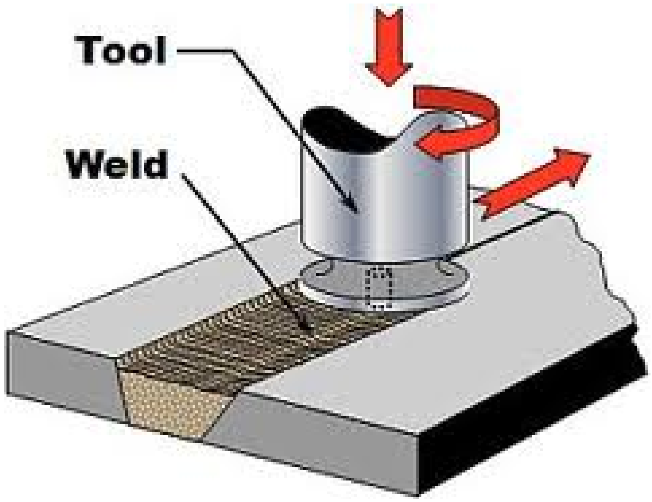


FSW Tool


Featureless Shoulder
Scrolled Shoulder
(viewed from underneath)
Shoulder
Pin
Threaded Pin
Threaded Pin
with Flutes

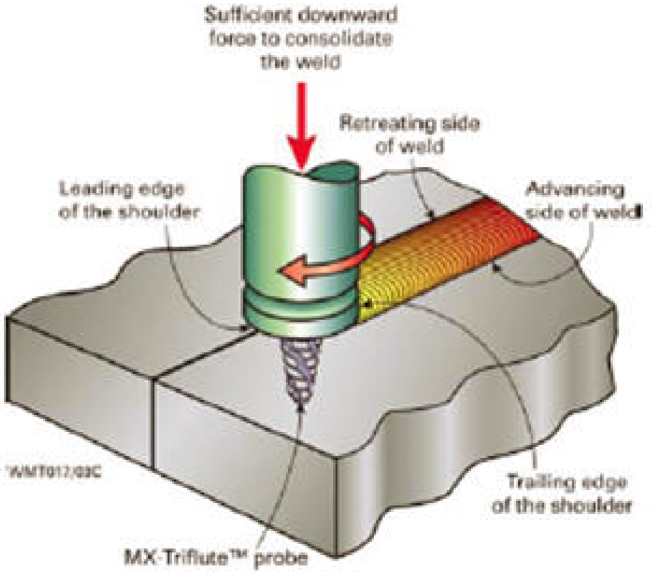
2.2 Friction stir welding (FSW),

- A rotating tool is fed along the joint line between two work pieces → Generates friction heat
- Mechanically stirring of the metal to form the weld seam
- The process derives its name from this stirring or mixing action
- FSW is distinguished from conventional FRW ⊥ Friction heat is generated by a separate wear-resistant tool rather than by the parts themselves



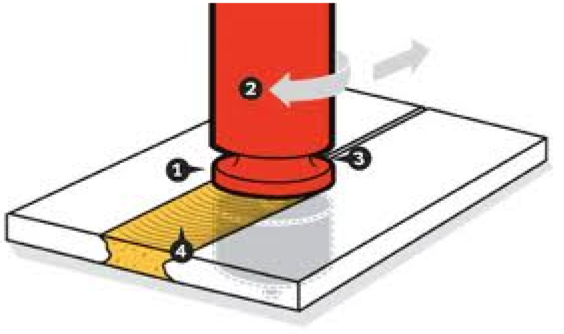
2.2 Friction stir welding (FSW),

- The rotating tool is stepped, consisting of a cylindrical shoulder and a smaller probe projecting beneath it
- The probe has a geometry designed to facilitate the mixing action
- The shoulder serves to constrain the plasticized metal flowing around the probe



2.2 Friction stir welding (FSW),

- During welding, the shoulder rubs against the top surfaces of the two parts, developing much of the friction heat
- While the probe generates additional heat by mechanically mixing the metal along the butt surfaces
- The heat produced by the combination of friction and mixing does not melt the metal but softens it to a highly plastic condition



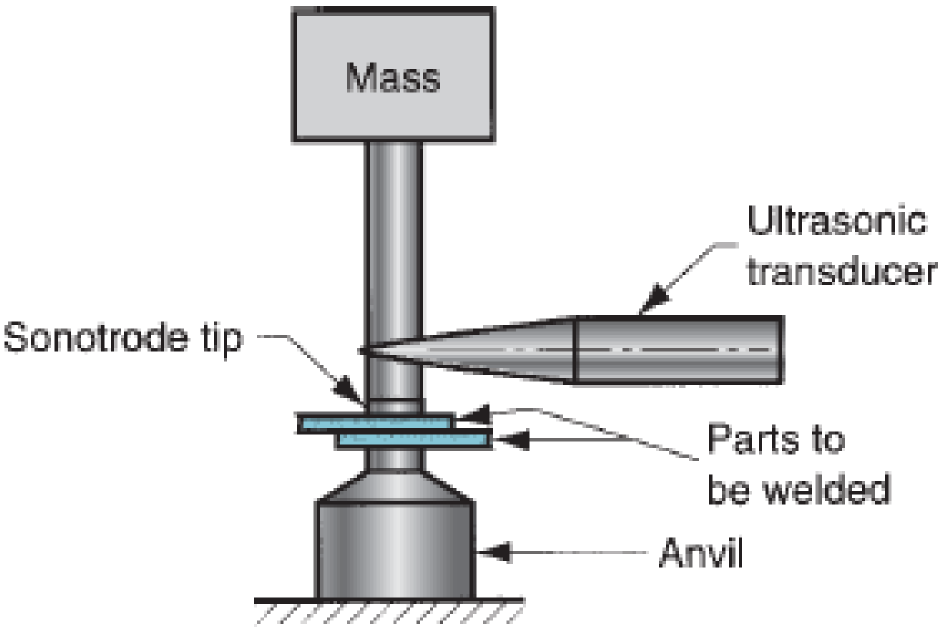
2.2 Friction stir welding (FSW),

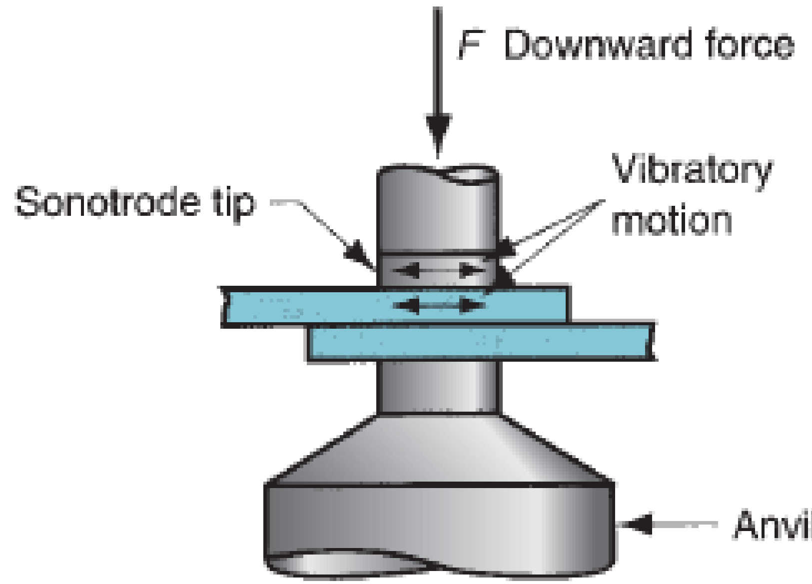
- Typical applications $\rightarrow$ butt joints on large aluminium parts
- Other metals, include steel, copper, and titanium, as well as polymers and composites
- Advantages of FSW
  - Good mechanical properties of the weld joint,
  - Avoidance of toxic fumes, warping, shielding issues, and other problems associated with arc welding,
  - Little distortion or shrinkage
  - Good weld appearance
- Disadvantages include
  - An exit hole is produced when the tool is withdrawn from the work, and
  - Heavy-duty clamping of the parts is required

Key benefits of friction stir welding

Metallurgical benefits	Environmental benefits	Energy benefits
1. Solid phase process 2. Low distortion of work piece 3. Good dimensional stability and repeatability 4. No loss of alloying elements 5. Excellent metallurgical properties in the joint area 6. Fine microstructure 7. Absence of cracking 8. Replace multiple parts joined by fasteners	1. No shielding gas required 2. No surface cleaning required 3. Eliminate grinding wastes 4. Eliminate solvents required for degreasing 5. Consumable materials saving, such as rugs, wire or any other gases	1. Improved materials use (e.g., joining different thickness) allows reduction in weight 2. Only 2.5% of the energy needed for a laser weld 3. Decreased fuel consumption in light weight aircraft, automotive and ship applications

2.3 Ultrasonic welding (USW)





2.3 Ultrasonic welding (USW)

- Two components are held together under modest clamping force
- Oscillatory shear stresses of ultrasonic frequency are applied to the interface to cause coalescence
- Oscillatory motion between the two parts breaks down any surface films → allows intimate contact and strong metallurgical bonding between the surfaces

2.3 Ultrasonic welding (USW)

- The oscillatory motion is transmitted to the upper work part by means of a sonotrode, which is coupled to an ultrasonic transducer.
- This device converts electrical power into high-frequency vibratory motion. Typical frequencies used in USW are 15 to 75 kHz, with amplitudes of 0.018 to 0.13mm
- Although heating of the contacting surfaces occurs due to interfacial rubbing and plastic deformation, the resulting temperatures are well below the melting point
- No filler metals, fluxes, or shielding gases are required in USW.

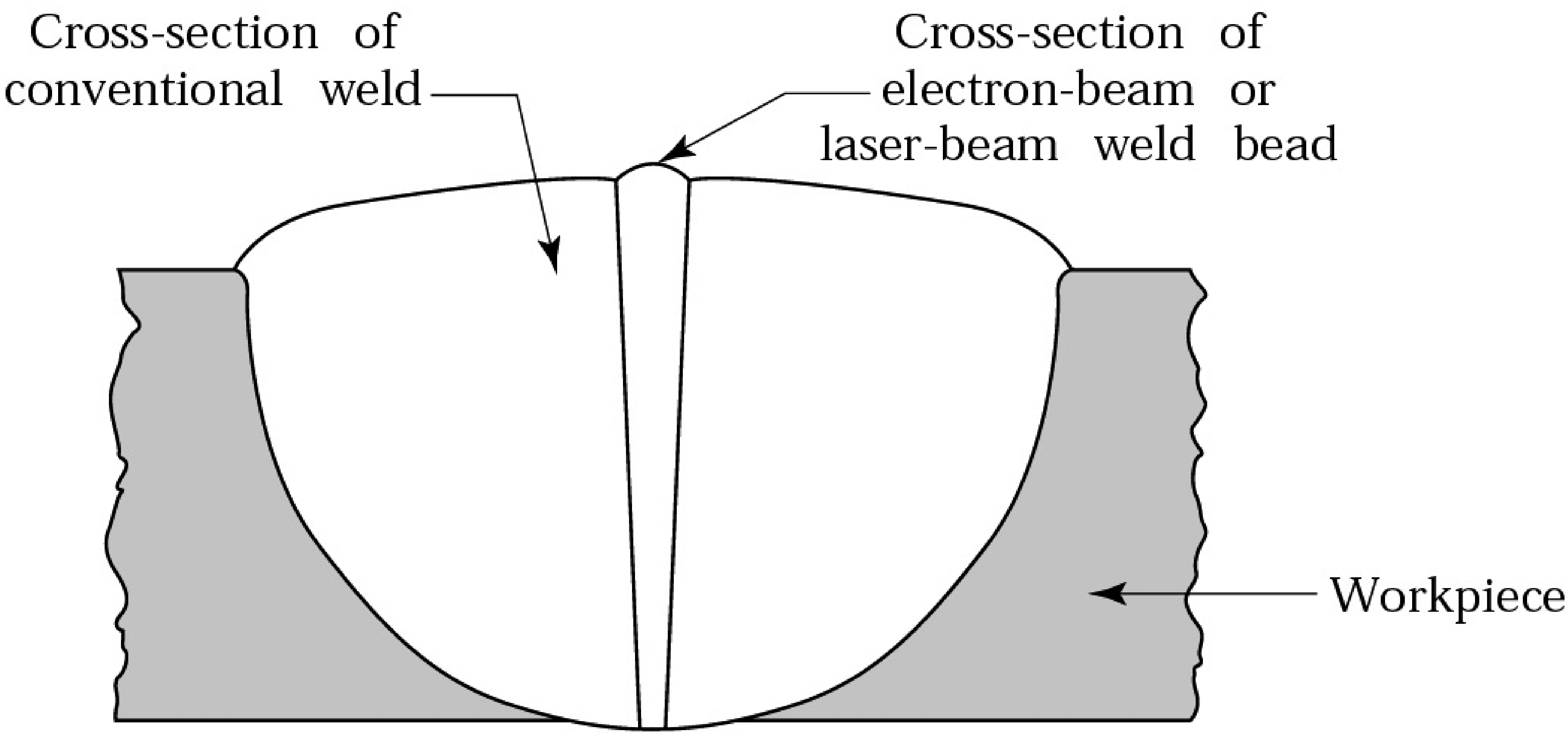
2.3 Ultrasonic welding (USW)

- Clamping pressures are well below those used in cold welding and produce no significant plastic deformation between the surfaces.
- Welding times under these conditions are less than 1 sec.
- USW operations are generally limited to lap joints on soft materials such as aluminum and copper.

High-Energy-Density Beam Welding Processes

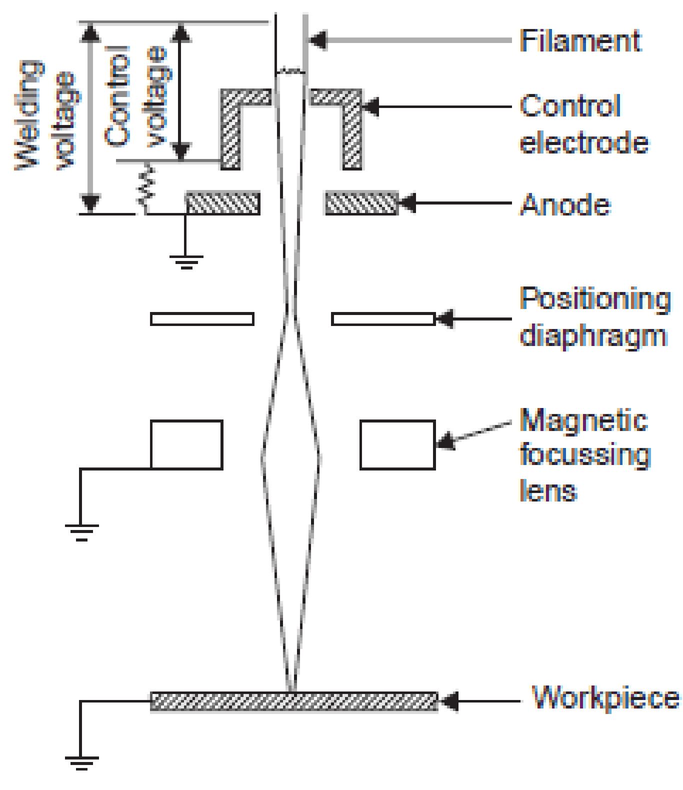
- Electron-beam and
- Laser-beam welding
- Focussed beam of electromagnetic energy
  - IR welding
  - Imaged arc welding
  - Microwave welding

Comparison of Conventional and E/Laser-Beam Welding

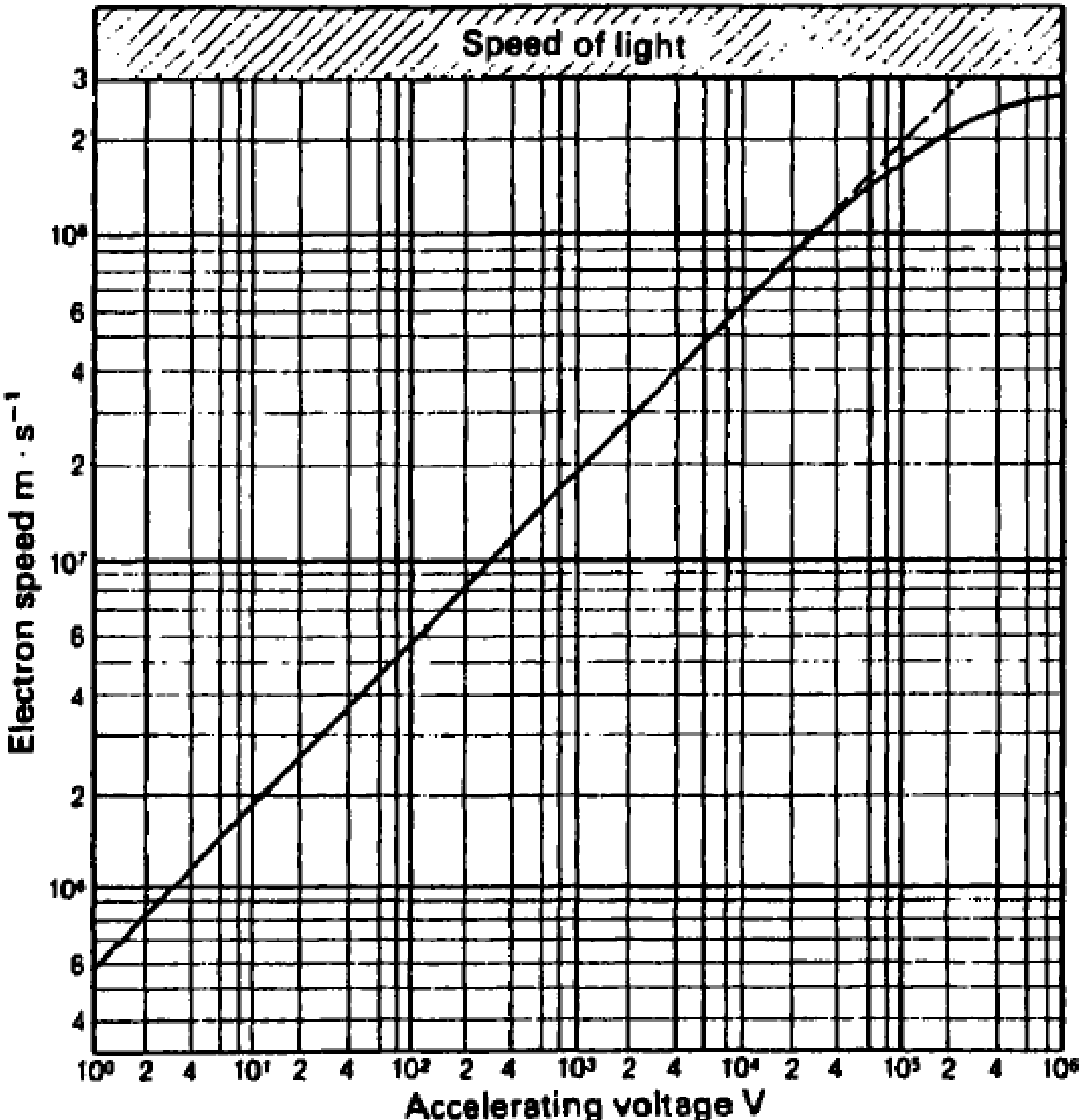


Electron-beam welding (EBW)

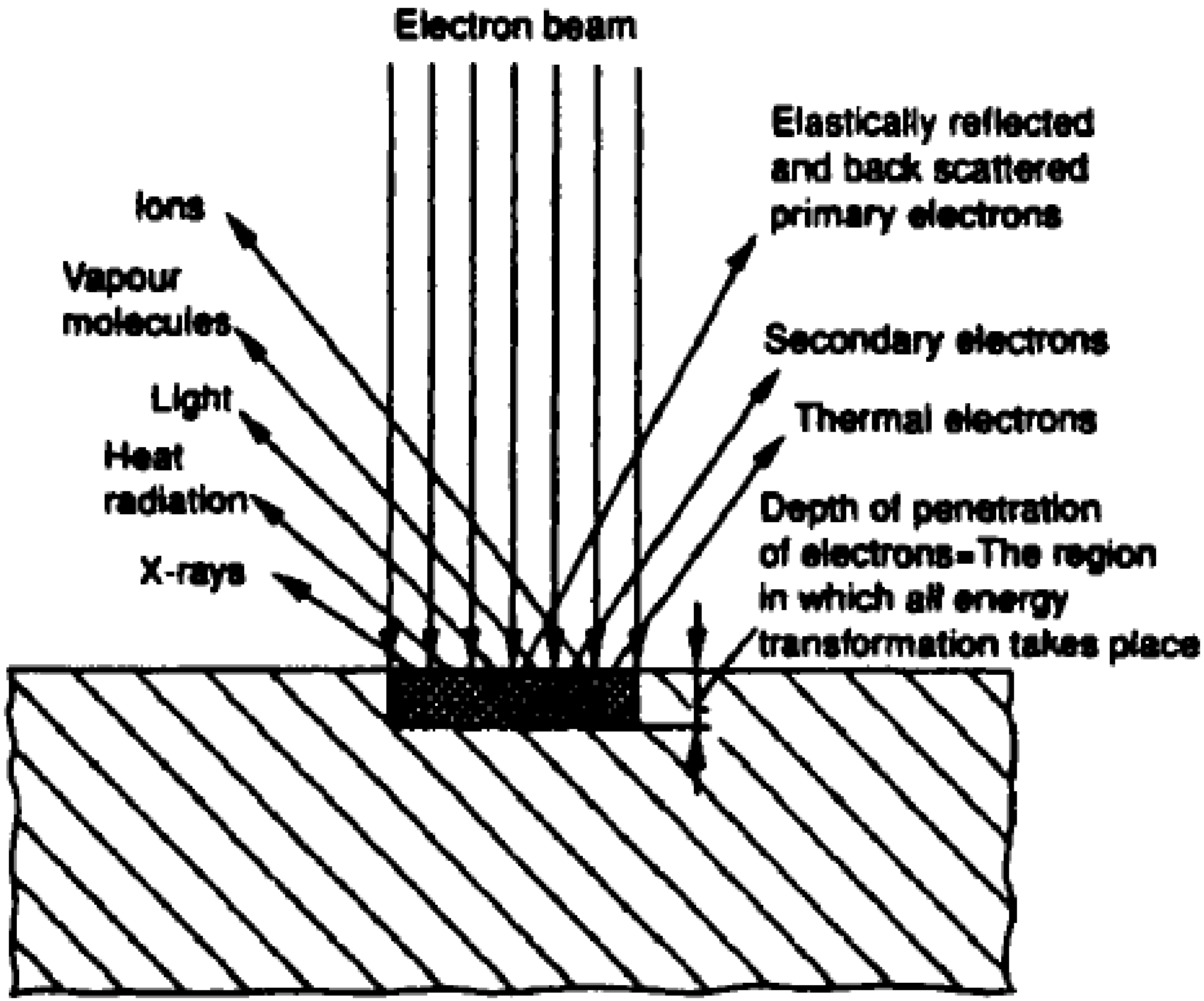
- Uses kinetic energy of dense focused electrons
- Electrons emitted by cathode, accelerated by ring shaped anode, focused by electromagnetic field
- High energy density 10 MW/mm^2
- Heat focus on few micrometers
- Vacuum chamber



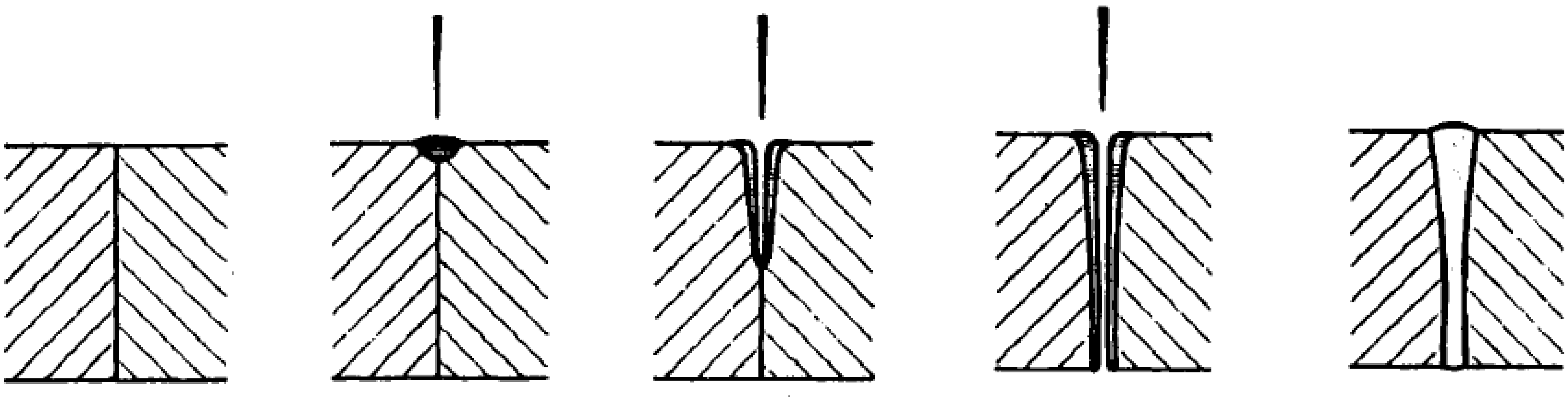
Electron speed Vs Accelerating voltage



E-Beam interaction with work piece



EBW or LBW of a butt joint



Butt joint prior to welding

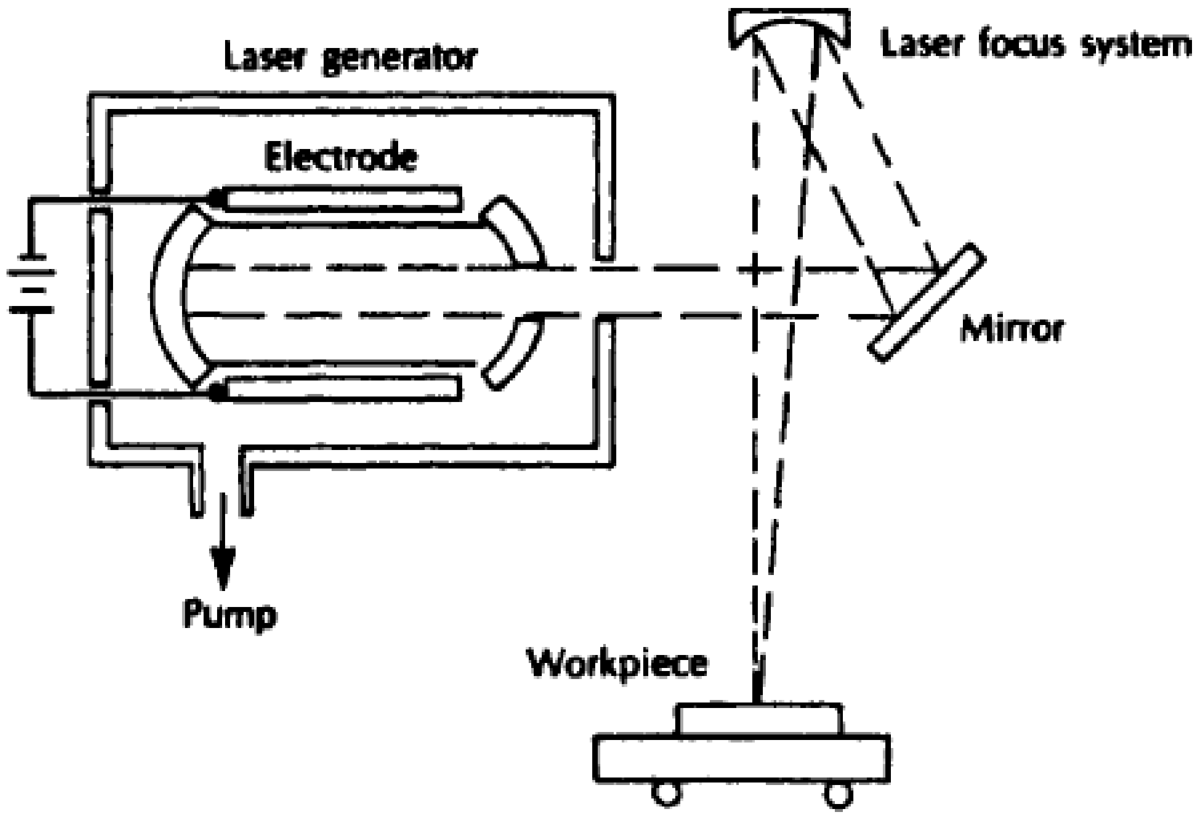
Melting occurs at the point of impingement of the E-beam

A key hole forms

The keyhole and its molten envelope penetrates workpiece

The weld forms upon solidification

Laser-beam welding (LBW)



Laser-beam welding

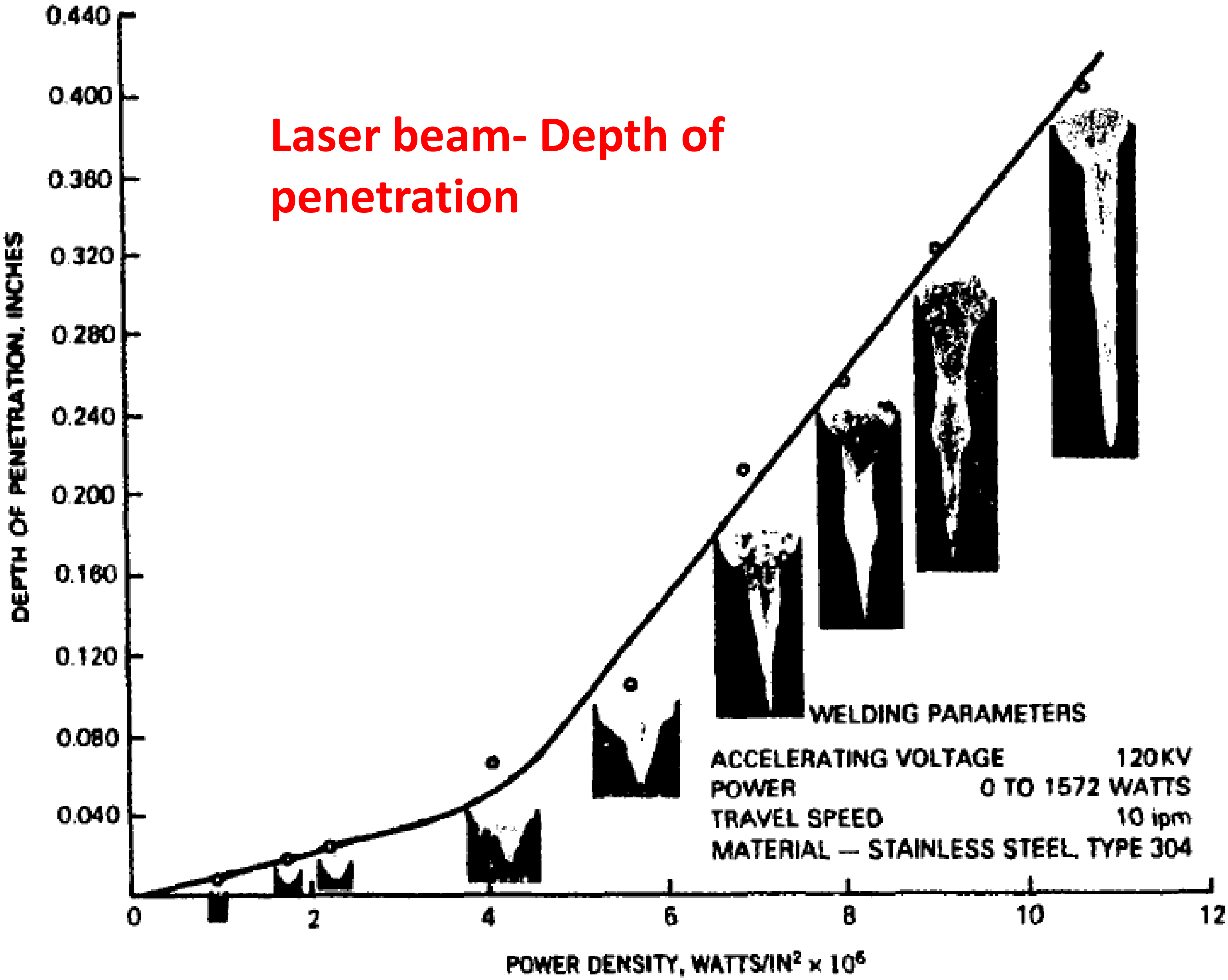
- Coalescence is achieved by the energy of a highly concentrated, coherent light beam focused on the joint to be welded
- LBW is normally performed with shielding gases (e.g., helium, argon, nitrogen, and carbon dioxide) to prevent oxidation
- No vacuum chamber is required, no X-rays are emitted
- Laser beams can be focused and directed by optical lenses and mirrors.
- LBW does not possess the capability for the deep welds and high depth-to-width ratios of EBW

Example-1

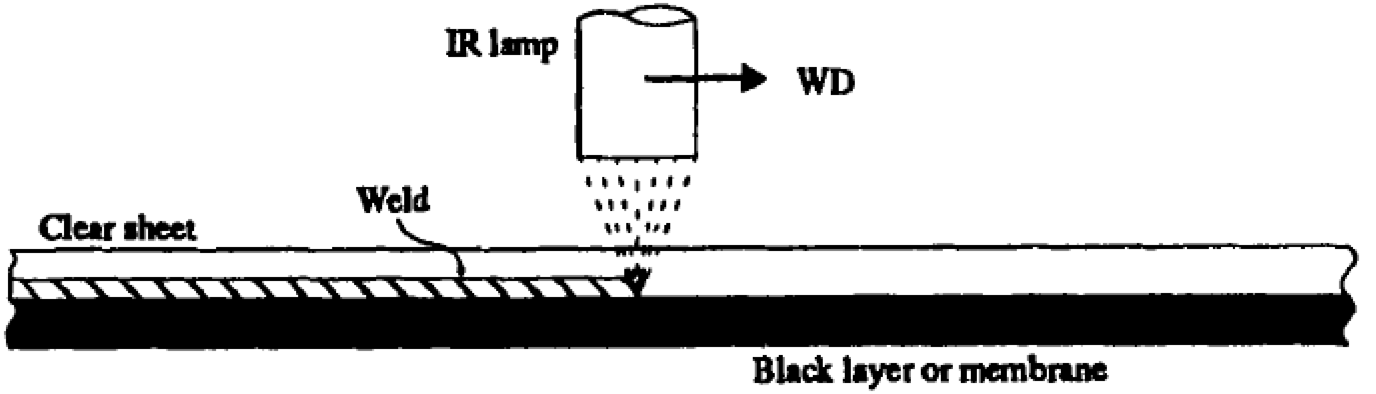
A carbon dioxide laser with a power output of 1 kW operates in the continuous wave mode. (For CO_2 laser, wavelength = 10 micron = 0.01 mm). Focal length f and diameter of the lens used is 100 mm and 8 mm respectively. The diameter of laser beam is 6 mm.

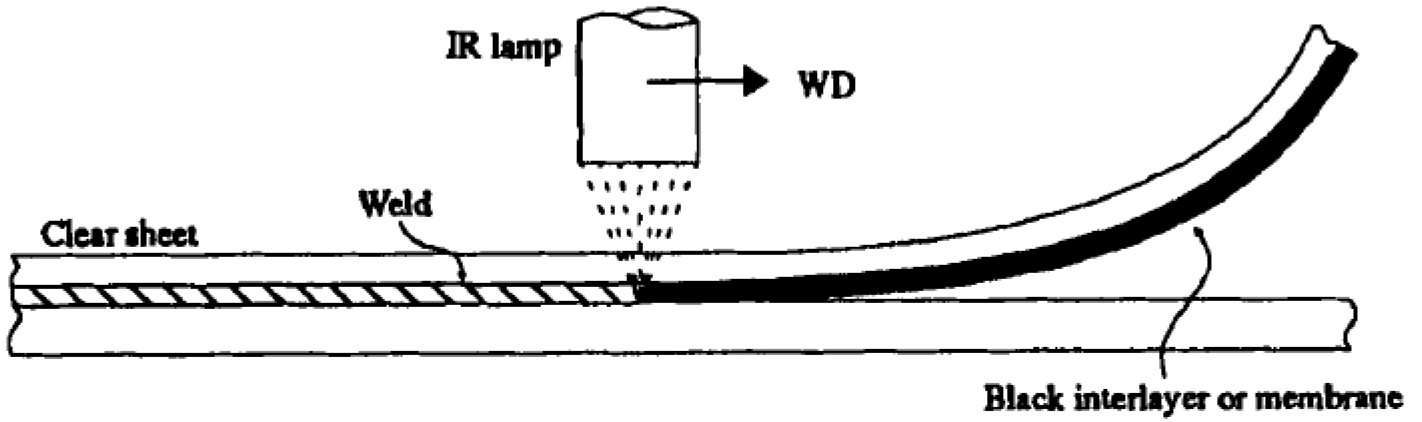
The laser-beam welding operation will join two pieces of steel plate together as shown in figure. The plates are 25 mm thick. The unit melting energy is 10 J/mm^3. The heat transfer factor is 0.70 and the melting factor is 0.55. Find the velocity of the laser beam movement if the beam penetrates the full thickness of the plates?

Laser beam- Depth of penetration



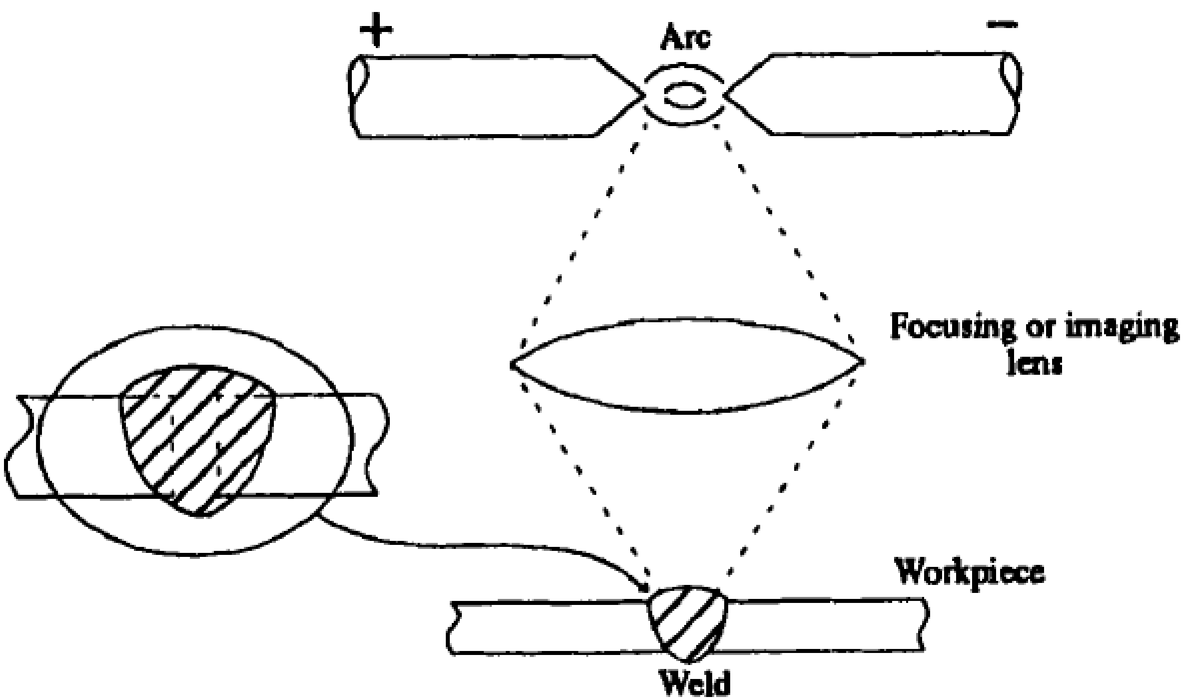
Focussed IR welding





- IR radiation from the sun or artificial light source can be used
- Radiation is focused into an intense, high-density spot directed onto the work

Imaging arc welding



- High energy density due to focussing
- Advantage is freedom from the electromotive Lorentz forces associated with conventional arc welding

Comparison of Electron-Beam and Laser-Beam Welding

EBW	LBW
1. Deep penetration in all materials	1. Deep penetration in many materials, but not in metals that reflect laser light/or of specific wavelengths
2. Very narrow welds	2. Can be narrow (in keyhole mode)
3. High energy density/low linear	3. Same
4. Best in vacuum, to permit electrons	4. Can operate in air, inert gas, or vacuum
5. Usually requires tight-fitting joints	5. Same
6. Difficult to add filler for deep welds	6. Same
7. Equipment is expensive	7. Same
8. Very efficient electrically (99%)	8. Very inefficient electrically (- 12%)
9. Generates x-ray radiation	9. No x-rays generated