

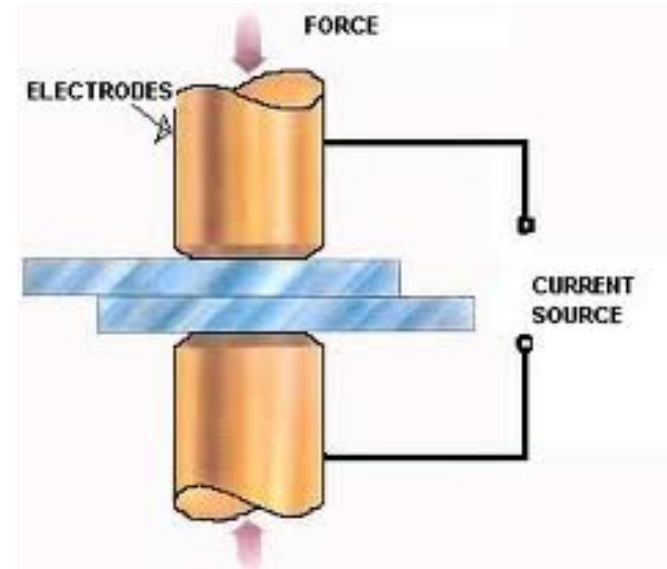
Welding Lecture - 9

16 August 2016, Tuesday 11.00 -11.50 am

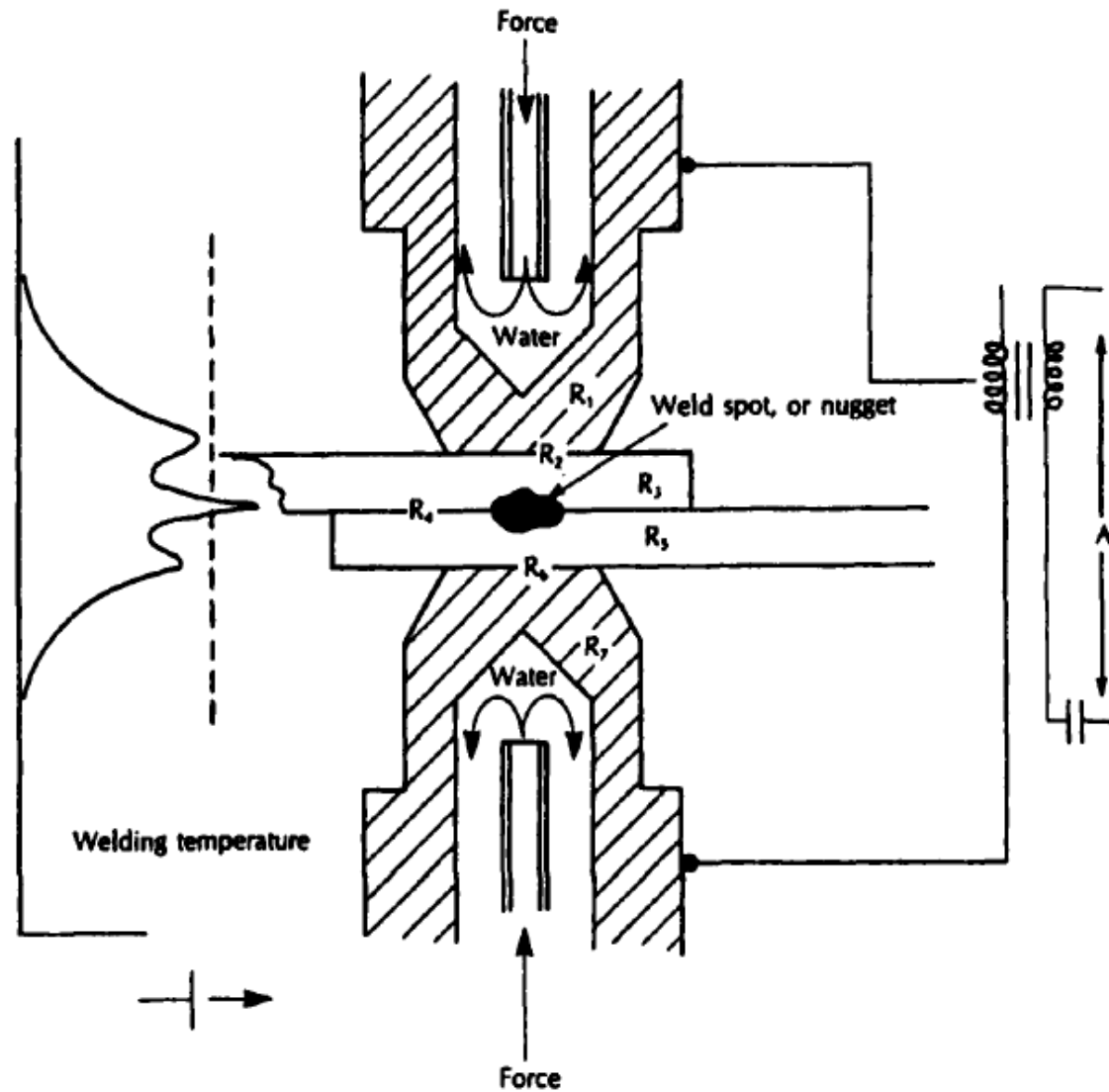
Welding Processes- Resistance welding

Resistance welding (RW)

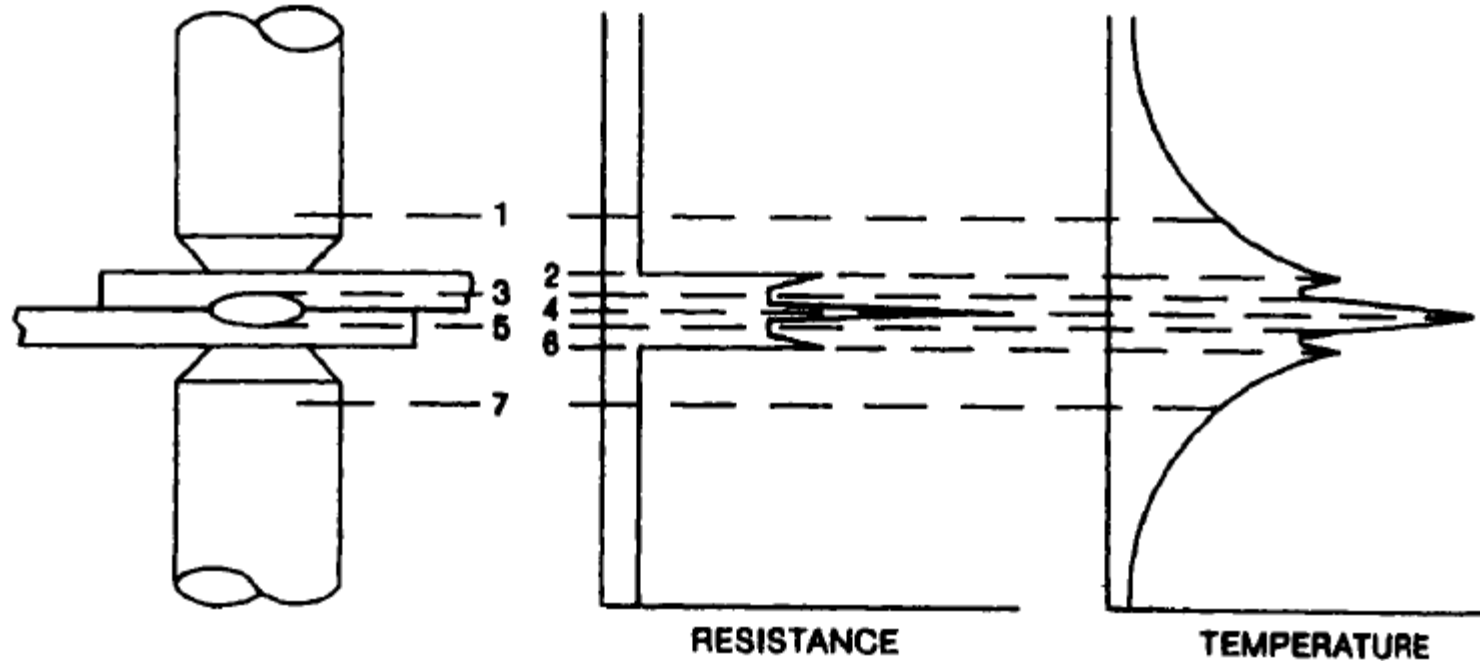
- Generate heat through the resistance to the flow of electric current in parts being welded
- The parts are usually an integral part of the electrical circuit
- Contact resistance \rightarrow heats the area locally by I^2R , \rightarrow melting \rightarrow formation of a nugget
- Contact resistance must be higher at the point to be welded than anywhere else.



Resistance welding



Resistance welding



$$Q = Pt = I^2 R t$$

$$\Delta T = \frac{Q}{m C_p} = \frac{I^2 R t}{m C_p}$$

Resistance welding

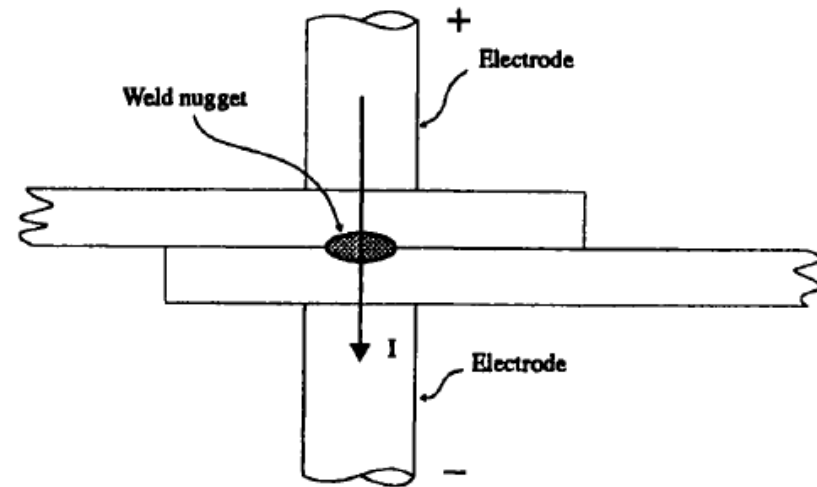
- Pairs of water-cooled copper electrodes
- Apply pressure
 - To reduce the contact resistance at the electrode-to-workpiece interface
 - Contain the molten metal in the nugget
 - To literally forge the work surfaces together in the vicinity of the weld
- The principal process variables
 - welding current (several thousands to tens of thousands of amperes)
 - welding time (of the order of s)
 - electrode force and electrode shape
- DC power (provided from either single-phase or three-phase AC line 440-480 V using step-down transformer/rectifiers)
- Usually used to join overlapping sheets or plates as lap joints, which may have different thicknesses

Resistance welding-types

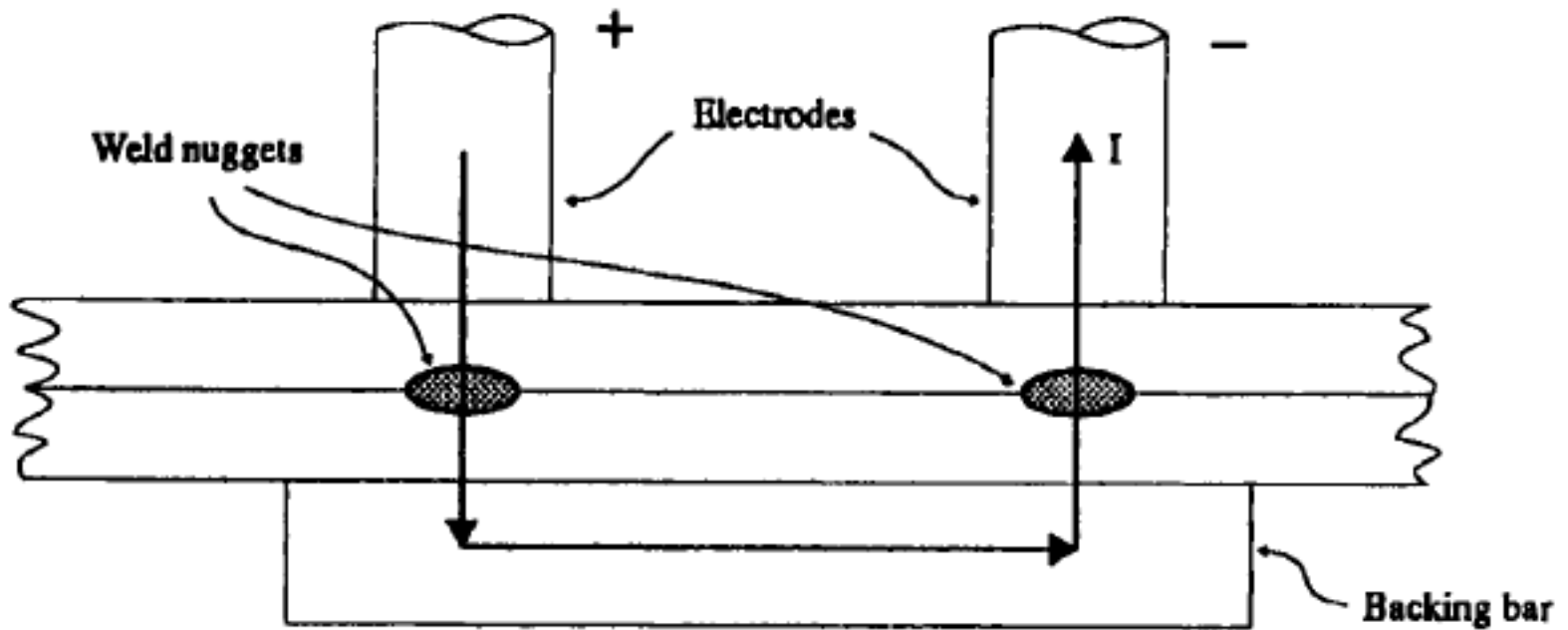
- Resistance spot welding (RSW)
- Resistance seam welding (RSEW)
- Projection welding (PW)
- Flash welding (FW)
- Upset welding (UW)
- Percussion welding (PEW)

Resistance spot welding (RSW)

- Series of discrete nuggets produced by resistance heating
- Nuggets (welds) are usually produced directly under the electrodes, → Not necessarily if there is another more favourable path (shunt), for the current



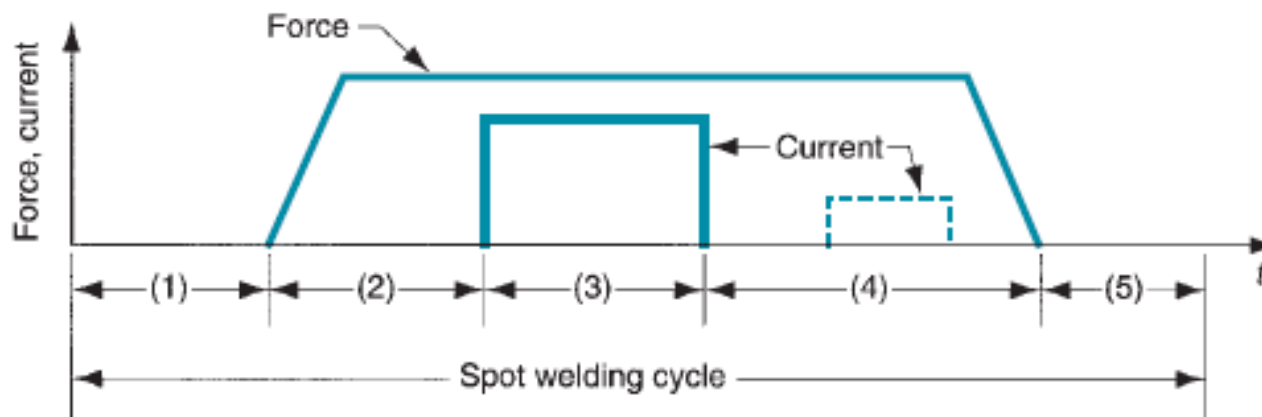
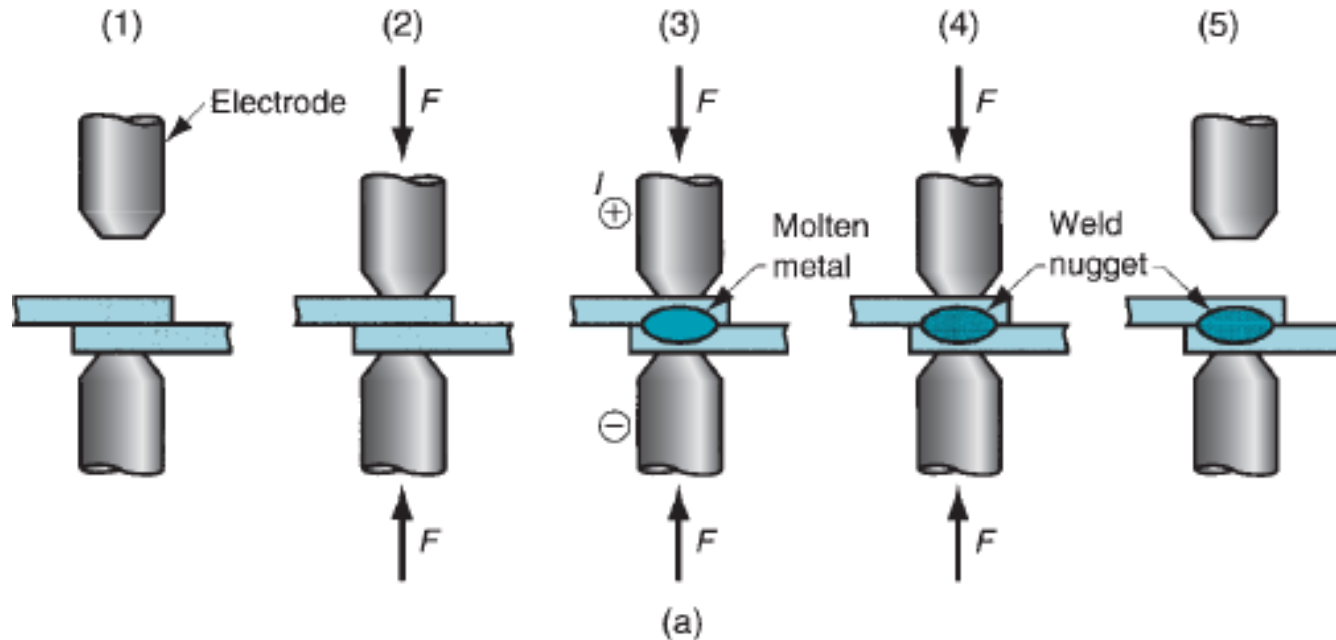
Series resistance spot welding



Resistance welding cycle

- Squeeze Time: Time interval between timer initiation and the first application of current needed to assure that electrodes contact the work and establish full force
- Weld time: The time for which welding current is applied (in single impulse welding) to the work
- Hold Time: The time during which force is maintained on the work after the last impulse of welding current ends to allow the weld nugget to solidify and develop strength.
- Off Time: The time during which the electrodes are off the work and the work is moved to the next weld location for repetitive welding.

Pressure-current cycle



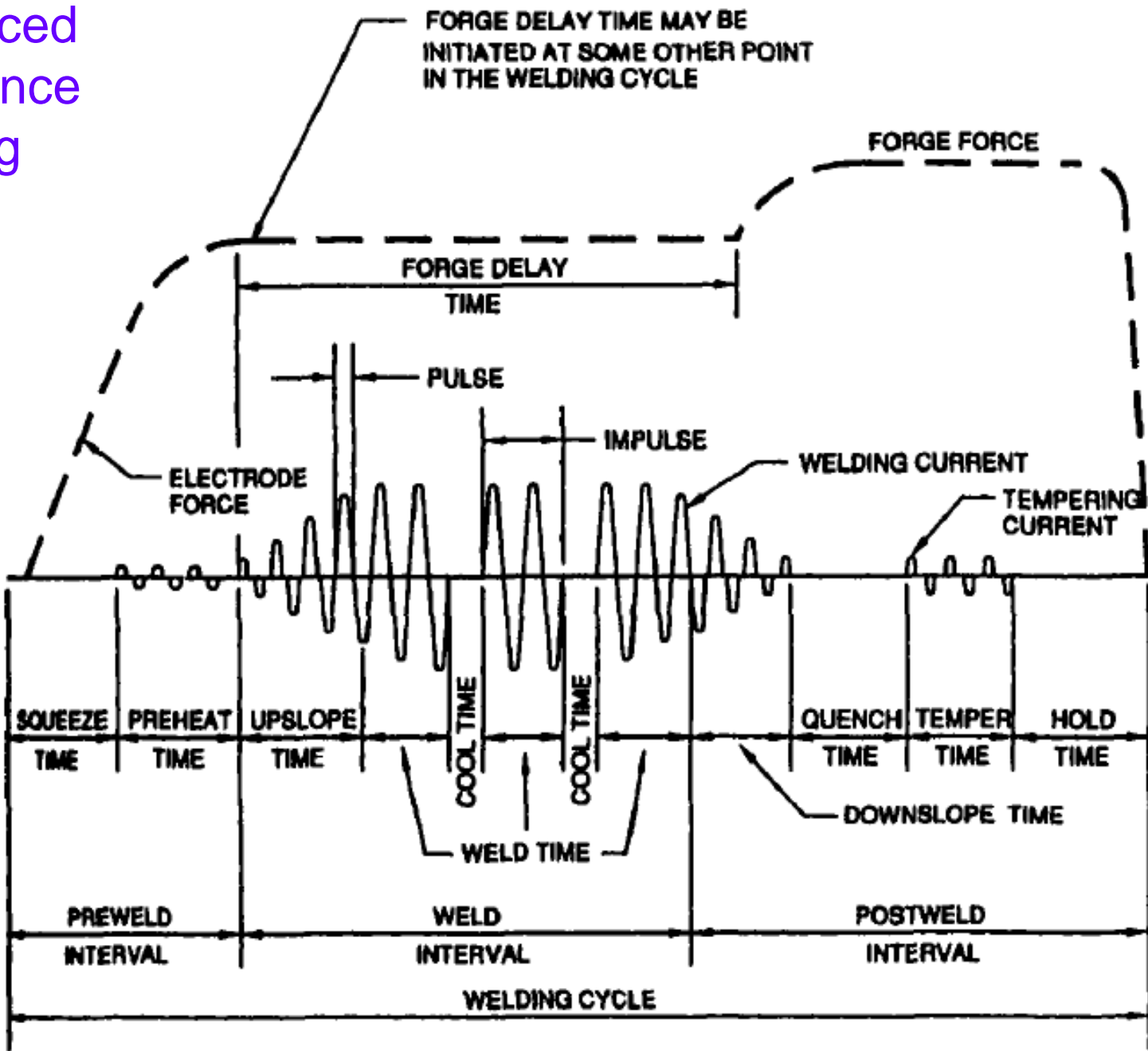
Pressure-current cycle

1. Off time: Parts inserted between open electrodes,
2. Squeeze Time: Electrodes close and force is applied,
3. Weld time— current is switched on,
4. Hold time: Current is turned off but force is maintained or increased (a reduced current is sometimes applied near the end of this step for stress relief in the weld region), and
5. Off time: Electrodes are opened, and the welded assembly is removed.

Enhanced welding cycle

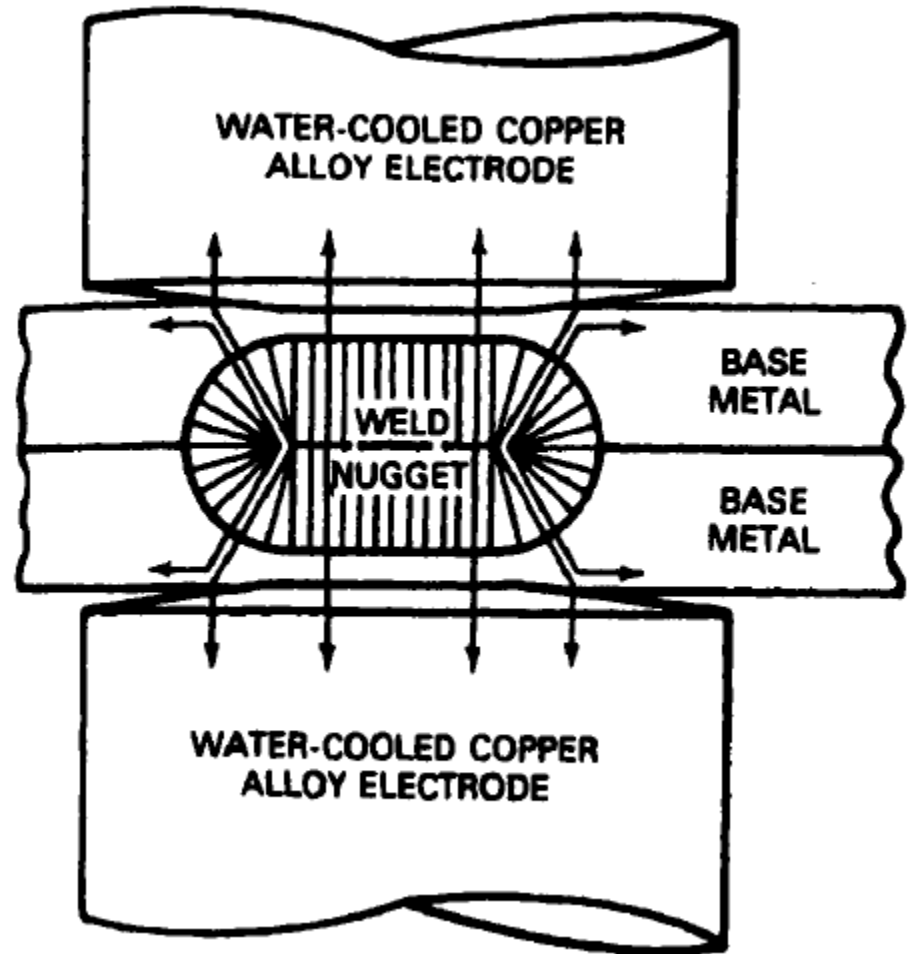
1. Pre-compression force is used to set electrodes and work pieces together
2. Preheat is applied to reduce thermal gradients at the start of weld time or to soften coatings
3. Forging force is used to consolidate weld nugget
4. Quench and temper times are used to produce desired weld properties in hardenable steels;
5. Post heat is used to refine weld nugget grain size and improve strength
6. Current decay is used to retard cooling of aluminum alloys to help prevent cracking

Enhanced
resistance
welding
cycle

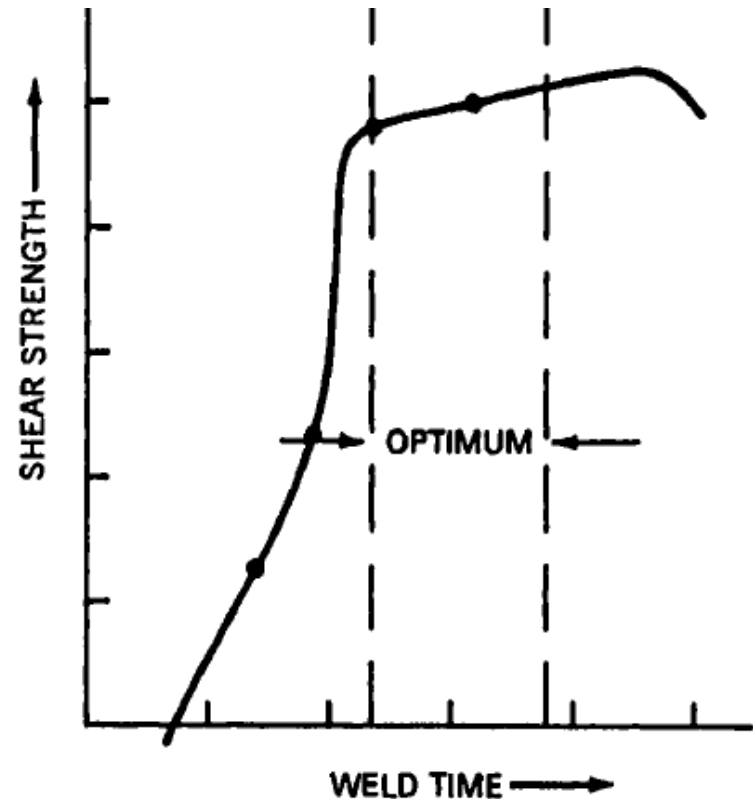
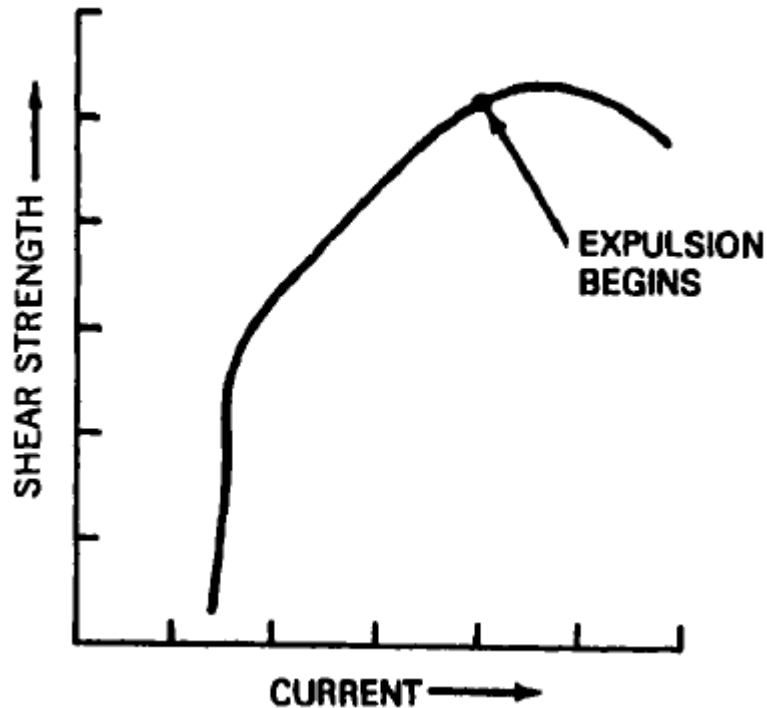


Nugget formation

Nugget formation and heat dissipation into the surrounding base metal and electrodes during resistance spot welding

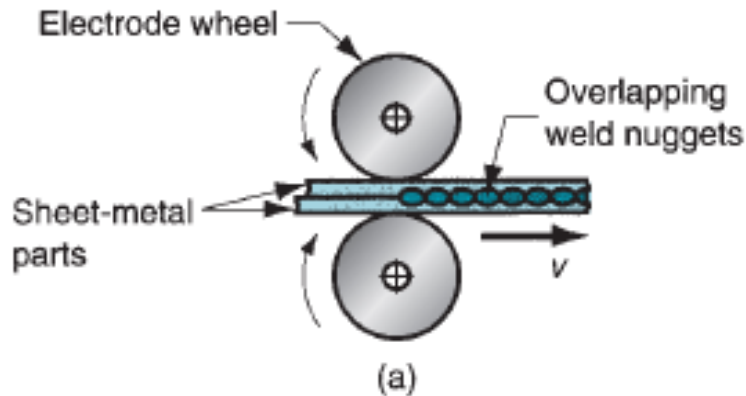


Optimum current, time in RW

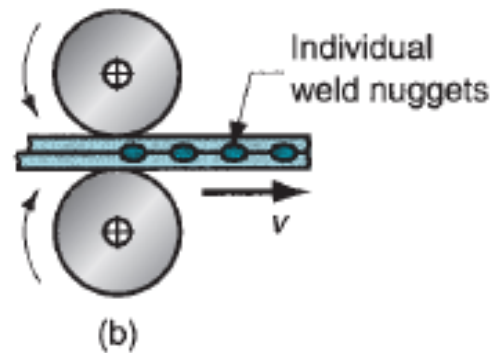


- Optimum current and weld time for maximum shear strength of the RW joint

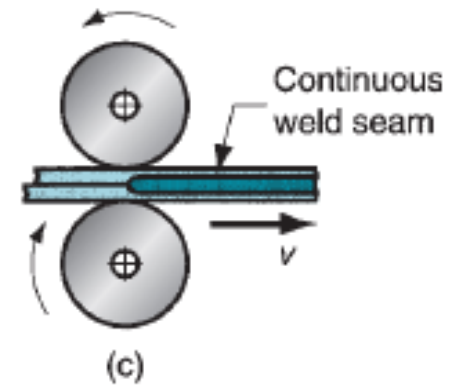
Resistance seam welding



Conventional
resistance seam
welding, in which
overlapping spots
are produced



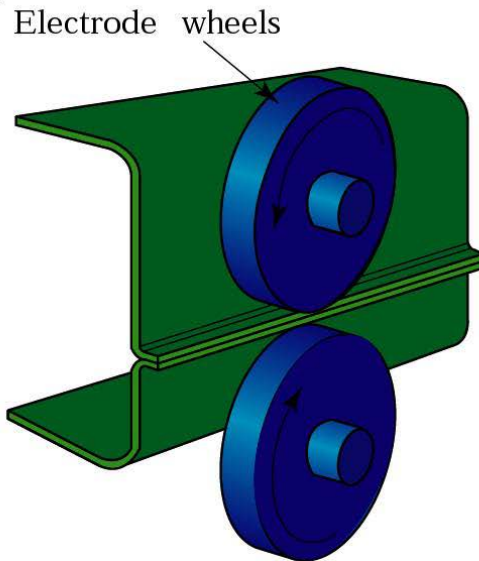
Roll spot
welding



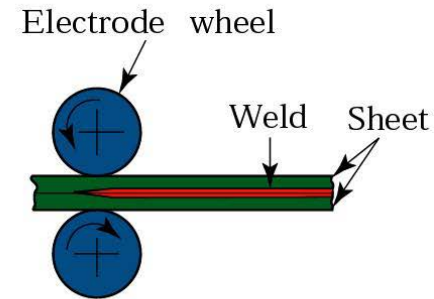
Continuous
resistance
seam

Resistance seam welding

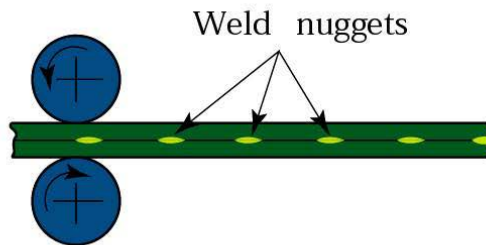
(a)



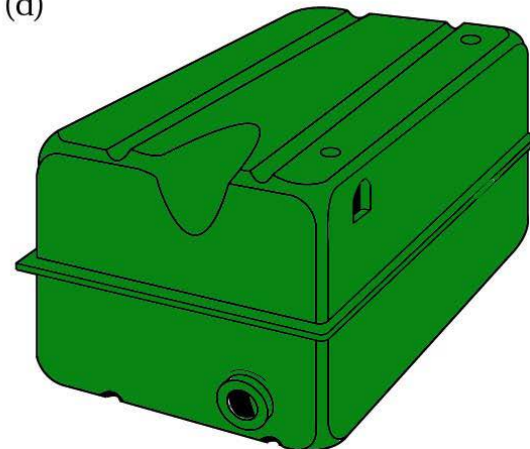
(b)



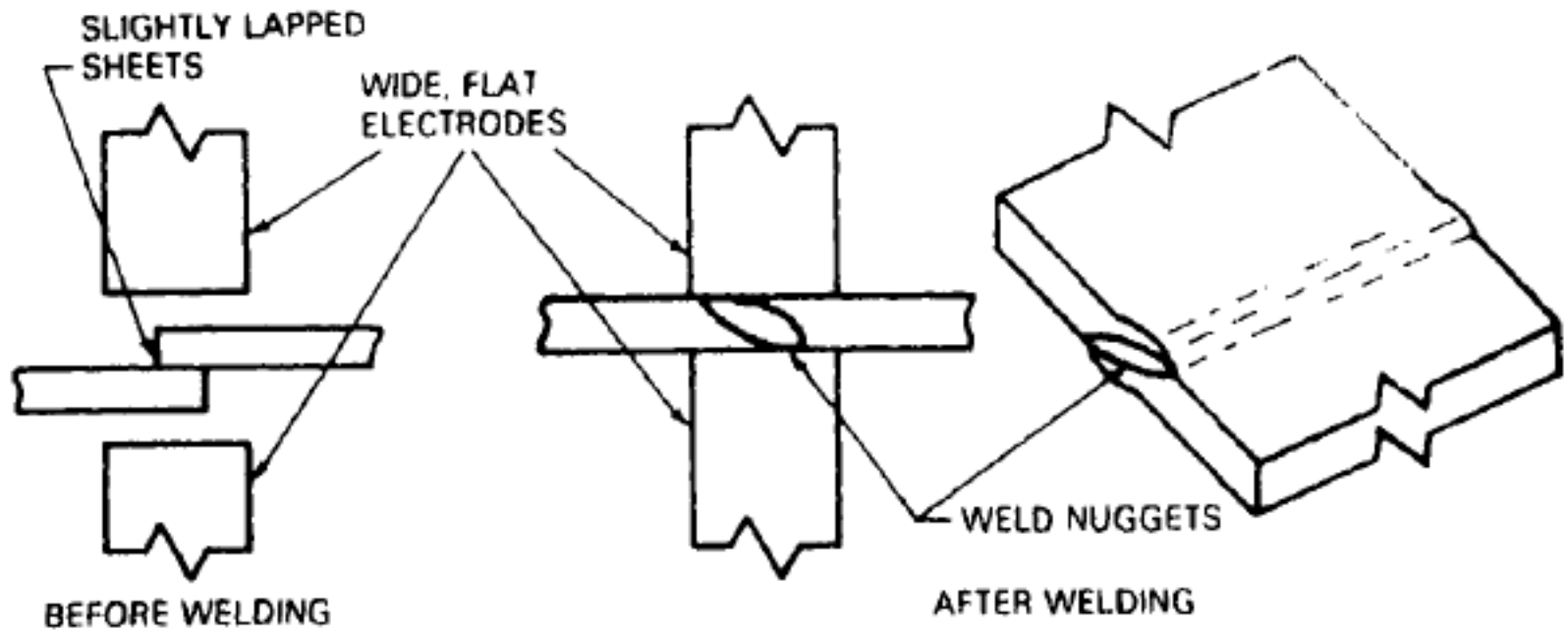
(c)



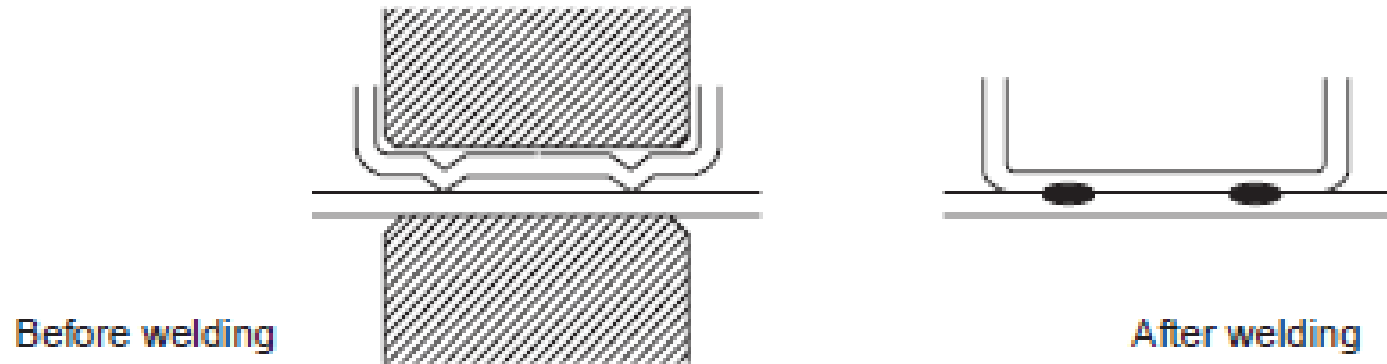
(d)



Mash seam weld

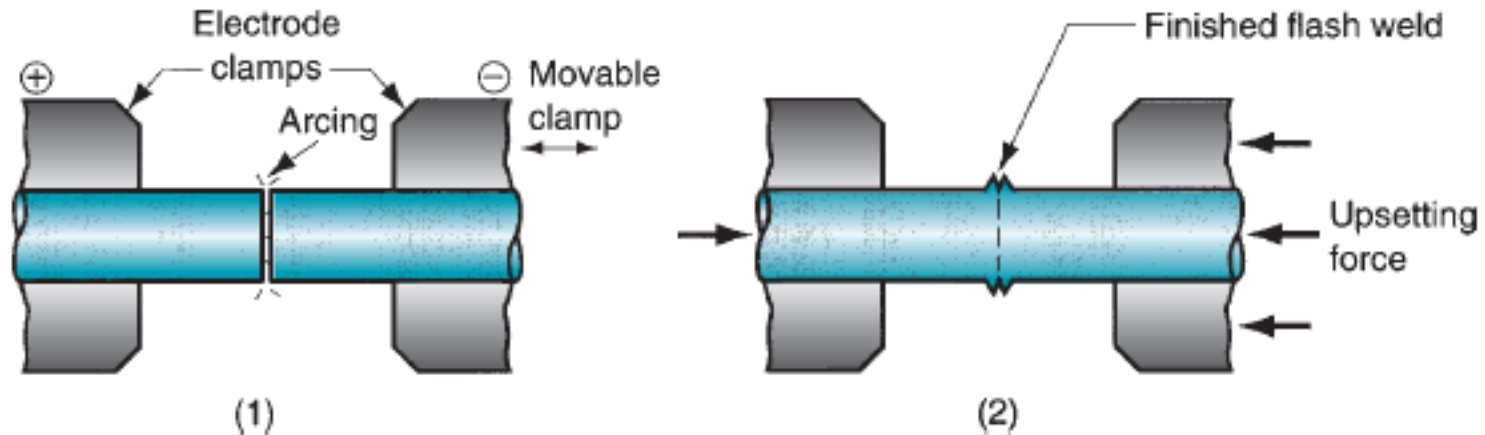


Projection welding (PW),



- Projections or dimples in overlapping joint elements → concentrate the current during welding, focusing the weld energy and helping to locate the weld more precisely
- Contact points determined by the design of the parts to be joined → may consist of projections, embossments, or localized intersections of the parts

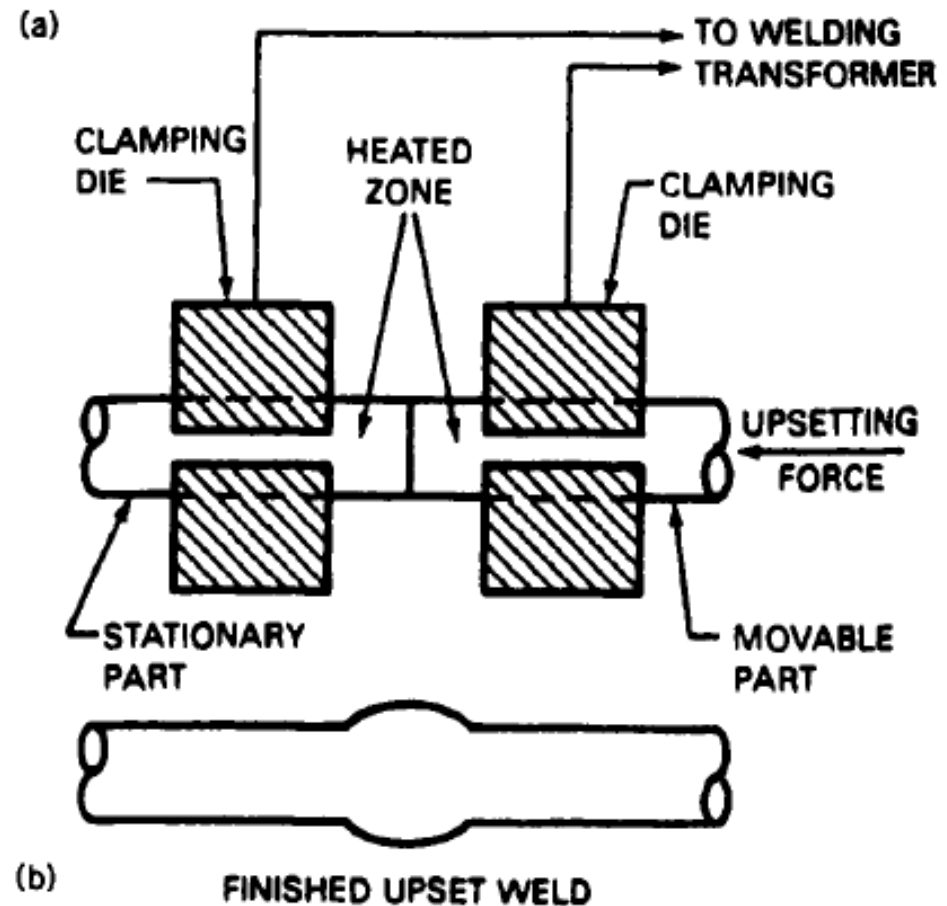
Flash welding(FW)



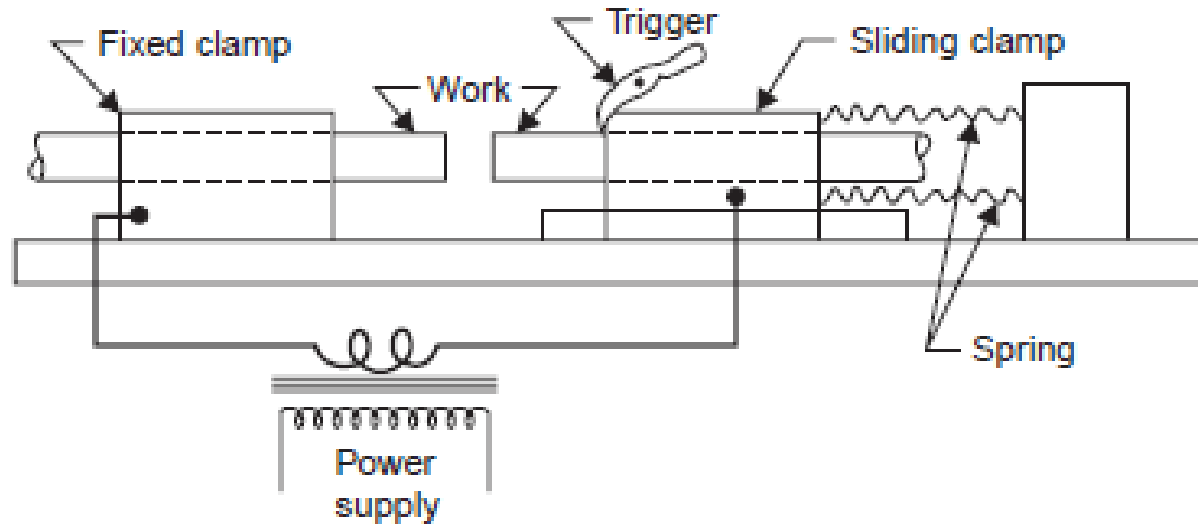
1. Normally used for butt joints → the two surfaces to be joined are brought into near contact →
2. Electric current is applied → Arcing → Heats the surfaces to the melting point → the surfaces are forced together to form the weld

Upset welding (UW)

- Upset welding (UW) is similar to flash welding
- Heating in UW is accomplished entirely by electrical resistance at the contacting surfaces; no arcing occurs.
- Not a fusion-welding process
- Applications of UW & FW- joining ends of wire, pipes, tubes etc.



Percussion welding

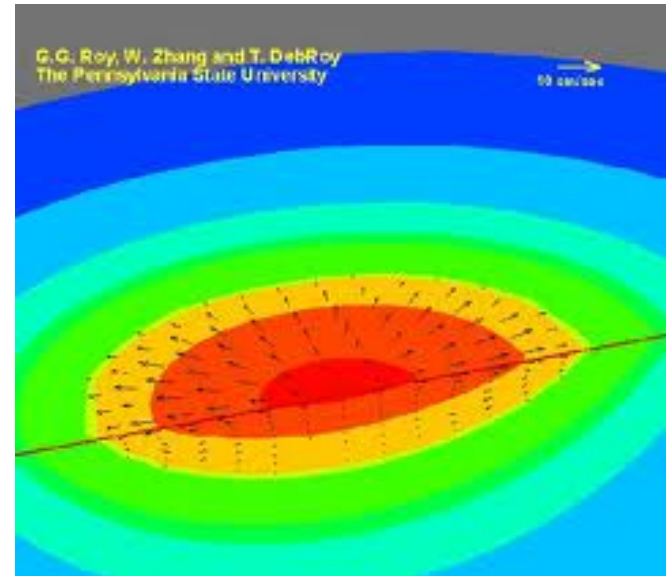


- Resistance heating by the rapid release of electrical energy from a storage device (e.g., capacitor).
- Similar to flash welding, except that the duration of the weld cycle is extremely short, ~ 1 to 10 ms
- Very localized heating \rightarrow attractive for electronic applications in which the dimensions are very small

Welding Lecture - 10

23 August 2016, Tuesday 11.00 -11.50 am

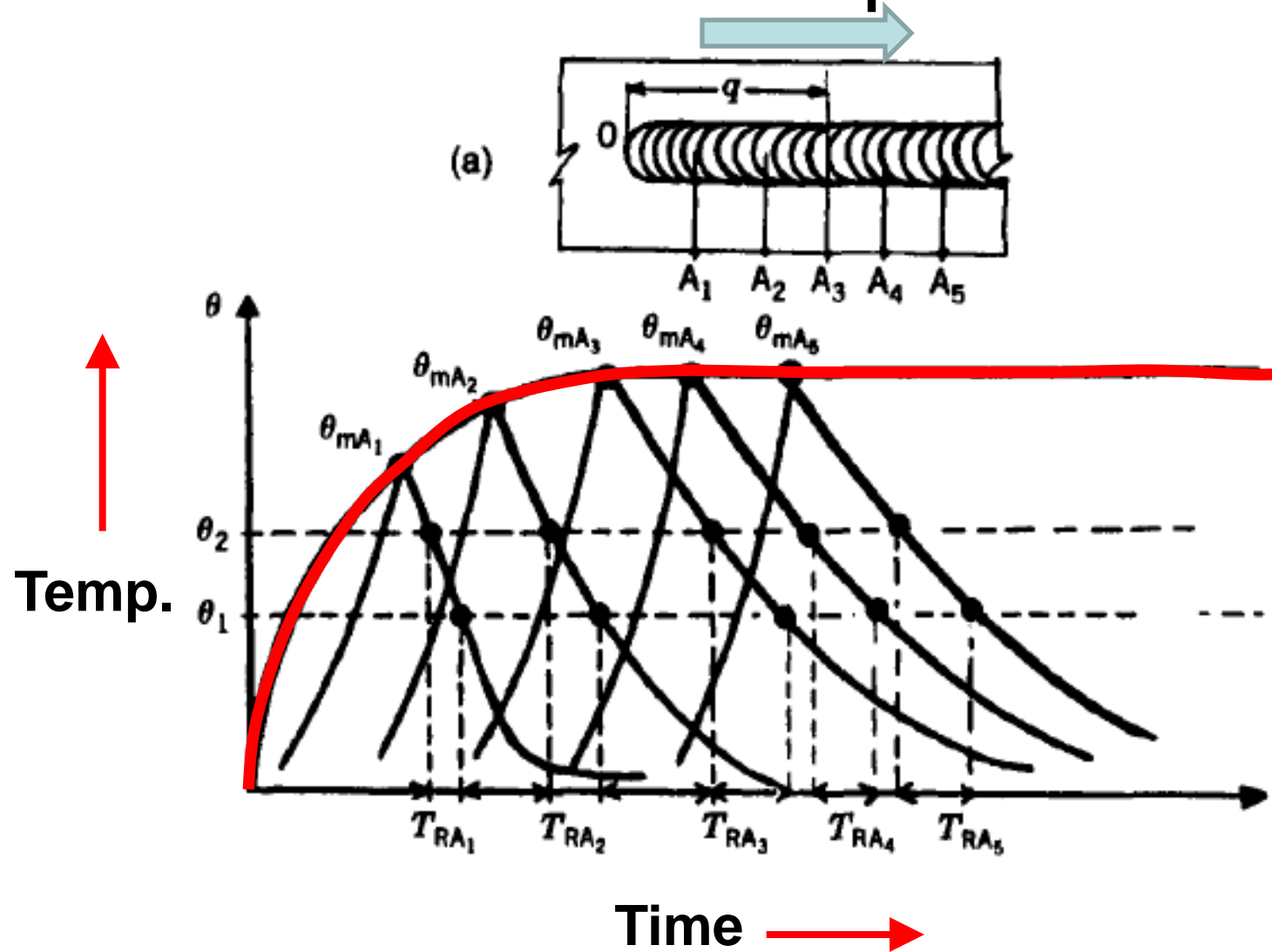
Heat flow in welds



The welding thermal cycle

- **Thermal excursion** → 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 → in terms of the
 - temp. reached
 - time taken to reach them
 - the time remain at themcompletely determines the effects on structure (both microstructural for material changes and macrostructural for distortion)
- To quantify the thermal cycle mathematically, we need temp. distribution in time and space coordinates

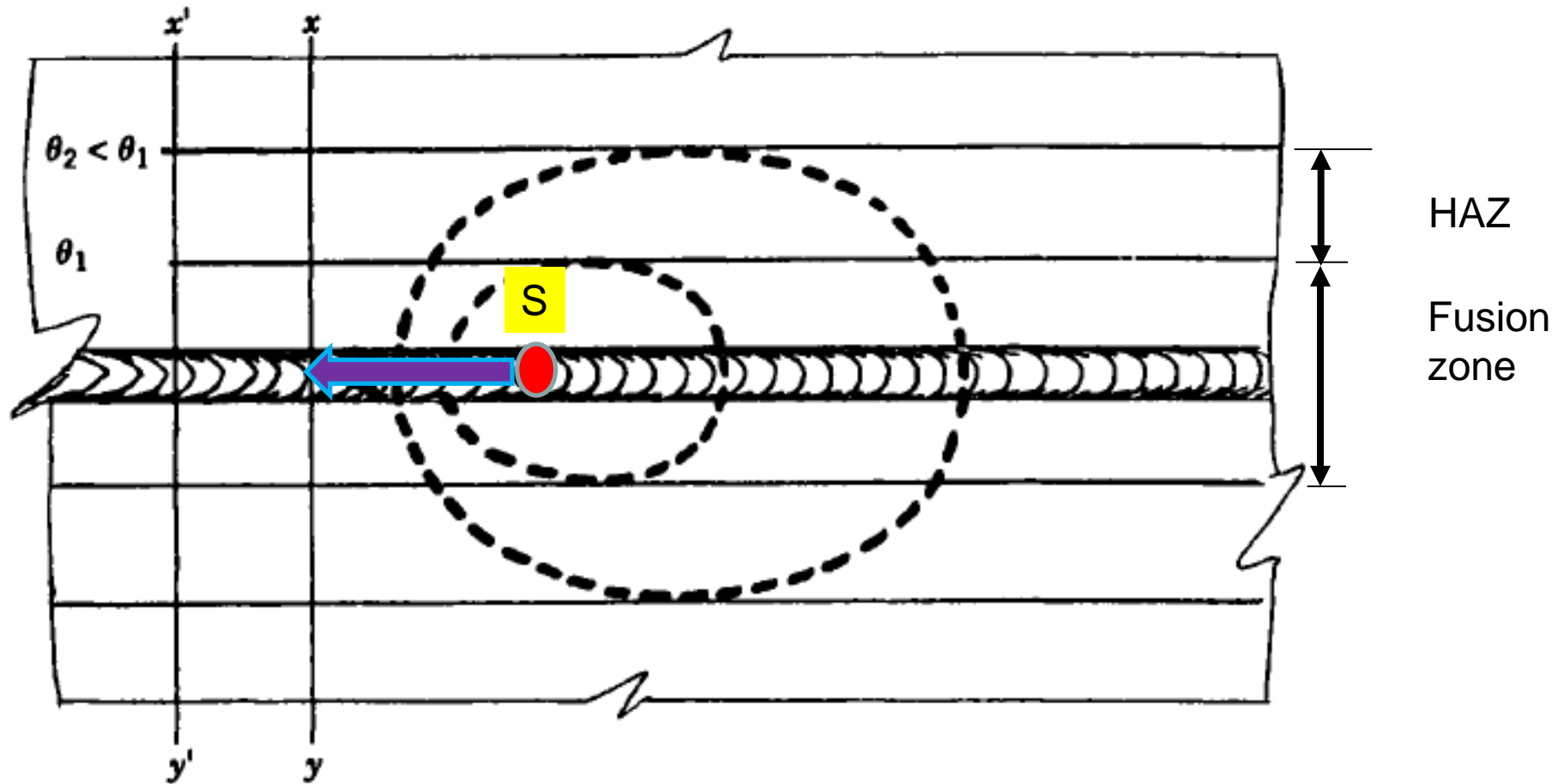
Thermal cycle characterization via thermocouples



Thermal cycle- quasi-steady state

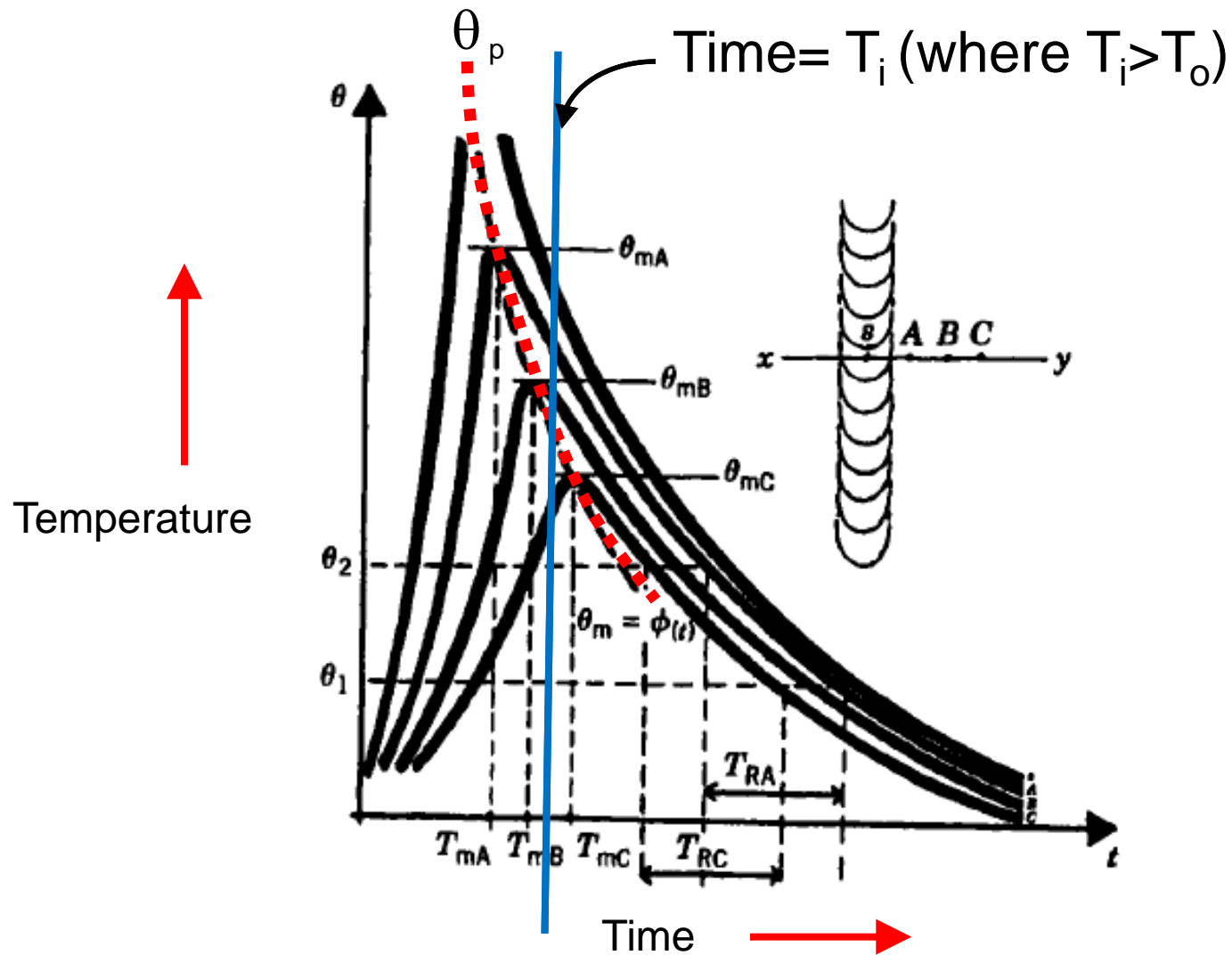
- Thermocouples → at various points along weld path
- Approach of the heat source → rapid rise in temperature to a peak → a very short hold at that peak → then a rapid drop in temperature once the source has passed by
- A short time after the heat from the source begins being deposited, → the peak temperature & rest of the thermal cycle, reaches a quasi-steady state
- Quasi-steady state → balance achieved between the rate of energy input and the rate of energy loss or dissipation
- Quasi-steady state → 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

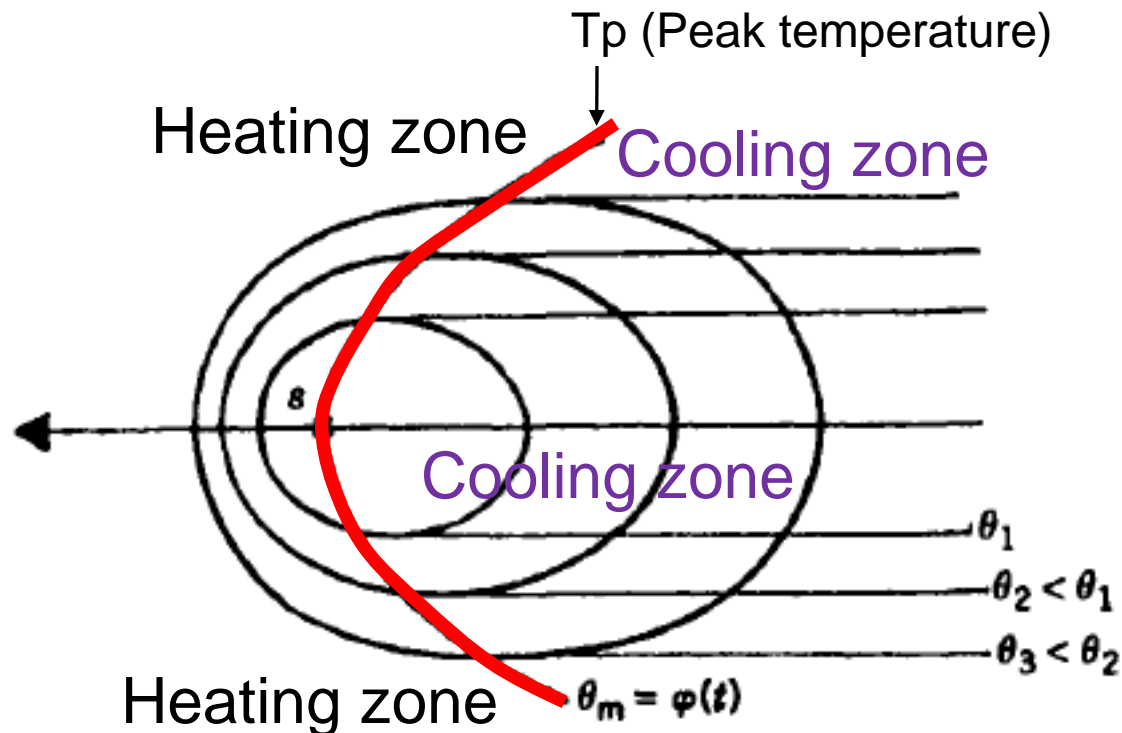
Time-Temperature curves



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



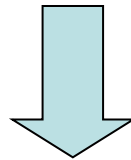
- Peak temperature separates the heating zone & cooling zone

The generalized heat flow equation

- Temp. distribution→ 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 ($\text{J/mm s}^{-1}\text{K}^{-1}$) 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 ($\text{J/g}^{-1}\text{K}^{-1}$), 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** → thin plate or sheet with a stationary source or for welding under steady state (at constant speed and in uniform cross sections remote from edges) in very thin weldments
- **2-D solution** → 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** → 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)

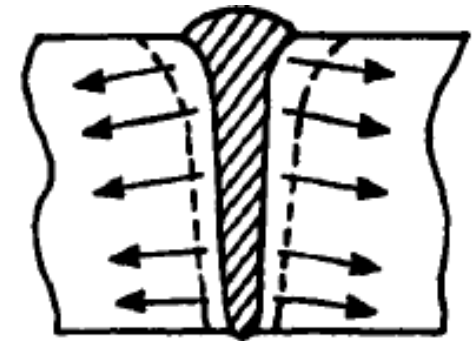
Weld geometry and dimensionality of heat flow

(a) 2-D heat flow for full-penetration welds in thin plates or sheets;



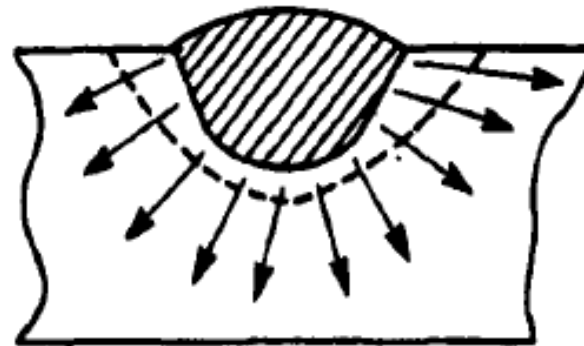
(a)

(b) 2-D heat flow for full-penetration welds with parallel sides (e.g. EBW & LBW)



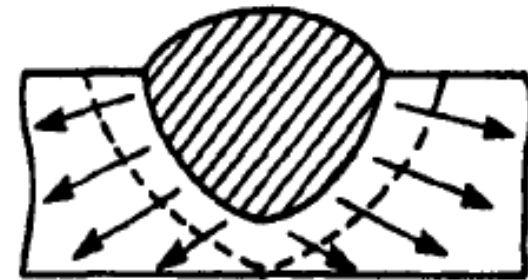
(b)

(c) 3-D heat flow for partial penetration welds in thick plate



(c)

(d) 3D, condition for near-full penetration welds (non parallel sides)



(d)

Rosenthal's Simplified Approach

- **Rosenthal's first critical assumption** → 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 these conditions is given by

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

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 Simplified Approach

- The moving coordinate system → replace x with ξ (X_i), where ξ is the distance of the point heat source from some fixed position along the x axis, depending on the velocity of welding, v

$$\xi = x - vt$$

where t is the time

$$\frac{d^2 T}{d\xi^2} + \frac{d^2 T}{dy^2} + \frac{d^2 T}{dz^2} = -\frac{C\rho}{k} v \frac{dT}{d\xi} + \frac{C\rho}{k} \frac{dT}{dt}$$

Rosenthal's Simplified Approach

- This equation can be further simplified, in accordance with Rosenthal, if a quasi-stationary temperature distribution exists.
- Temperature distribution around a point heat source moving at constant velocity will settle down to a steady form, such that **$dT/dt = 0$** , for **$q/v = \text{a constant}$** . The result is

$$\frac{d^2 T}{d\xi^2} + \frac{d^2 T}{dy^2} + \frac{d^2 T}{dz^2} = -\frac{C\rho}{k} v \frac{dT}{d\xi}$$

Rosenthal's solution

- Rosenthal solved the simplified form of the heat flow equation above for both thin and thick plates in which the heat flow is basically 2-D and 3-D, respectively.
- For thin plates,

$$T - T_0 = \frac{q}{2\pi k} e^{-v\xi/2\alpha} K_0 \frac{vR}{2\alpha}$$

1

$q = \eta EI/v$ = heat input from the welding source (in J/m)

k = thermal conductivity (in J/m s⁻¹ K⁻¹)

α = thermal diffusivity = $k/\rho C$, (in m²/s)

$R = (\xi^2 + y^2 + z^2)^{1/2}$, the distance from the heat source to a particular fixed point (in m)

K_0 = a Bessel function of the first kind, zero order

Rosenthal's solution

- For the thick plate,

$$T - T_0 = \frac{q}{2\pi kd} e^{-v\xi/2\pi} \frac{e^{-vR/2\pi}}{R} \quad \text{-----} \quad \textcircled{2}$$

where d = depth of the weld (which for symmetrical welds is half of the weld width, since $w = 2d$)

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 $r^2 = z^2 + y^2$
- For the thin plate, the time-temperature distribution is

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

and for the thick plate is

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

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 ($k/\rho C$) 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_0 = temperature of the workpiece at the start of welding.

For a symmetrical weld bead, the width of the weld bead $w = 2d$,

→ 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

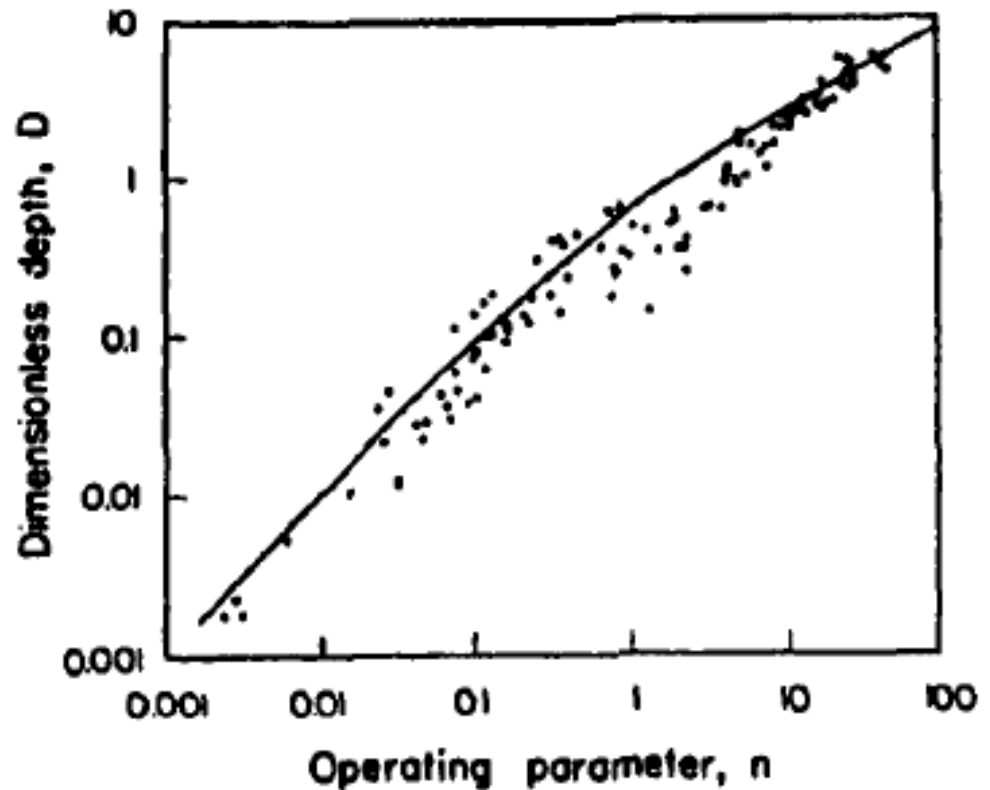
Dimensionless weld depth (D) Vs process operating parameter n

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 $T_m = 1510\text{ C}$

$E = 20\text{ V}$

$I = 200\text{ A}$

Welding speed (v or U) = 5 mm/s

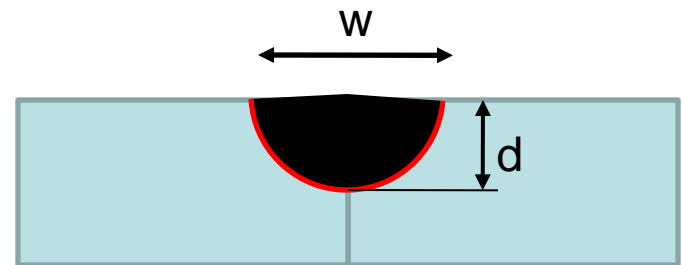
$T_0 = 25\text{ C}$

Arc efficiency $\eta = 0.9$

$K = 40\text{ W/mK}$

$\rho C = 0.0044\text{ J/mm}^3 \cdot \text{C}$

$t = 5\text{ mm}$



Effect of welding parameters on heat distribution

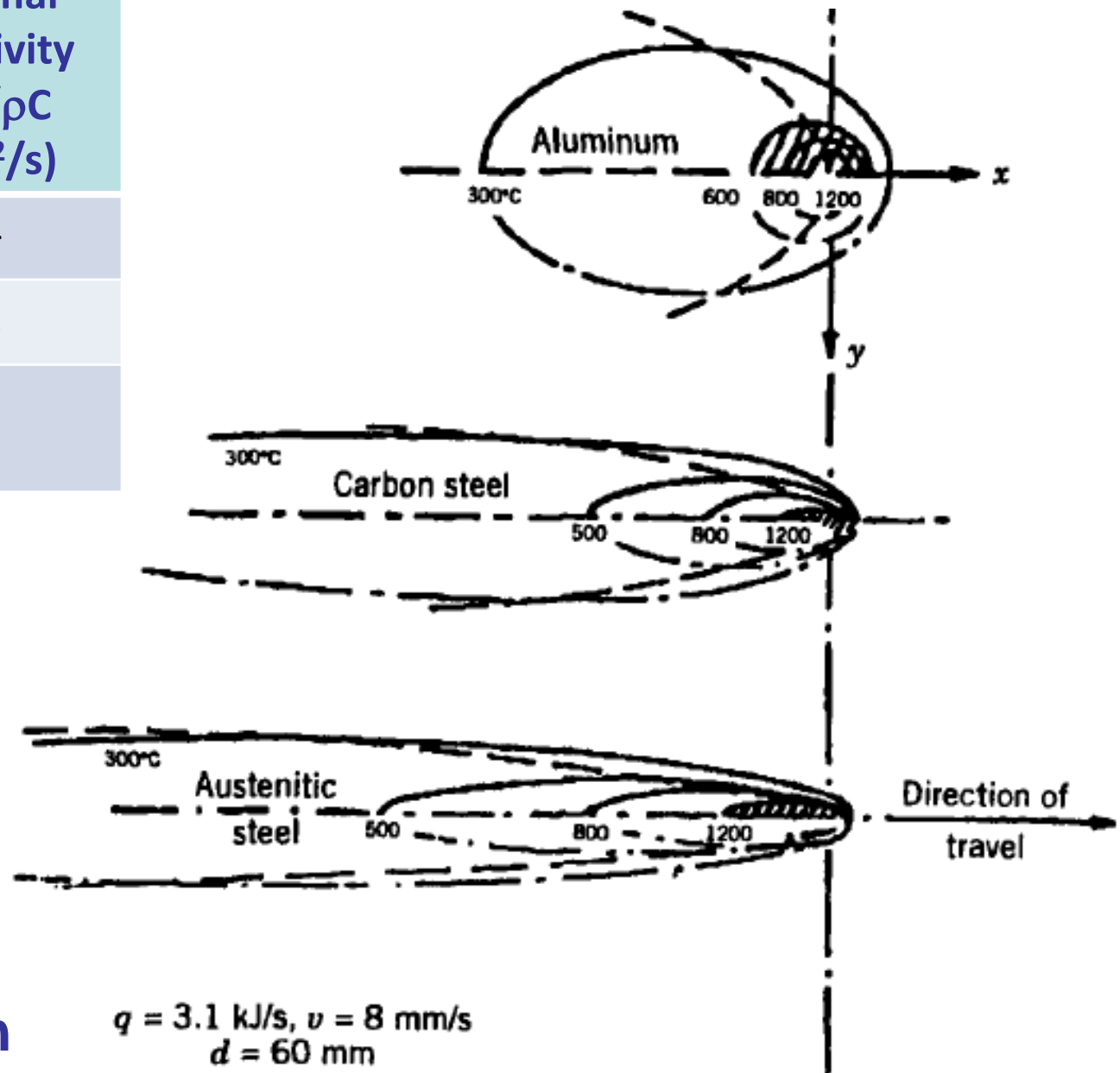
- The shape of the melt , size & heat distribution, is a function of
 1. Material properties (thermal conductivity, heat capacity, density)
 2. Welding speed, and
 3. Welding power/energy density
 4. Weldment plate thickness

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

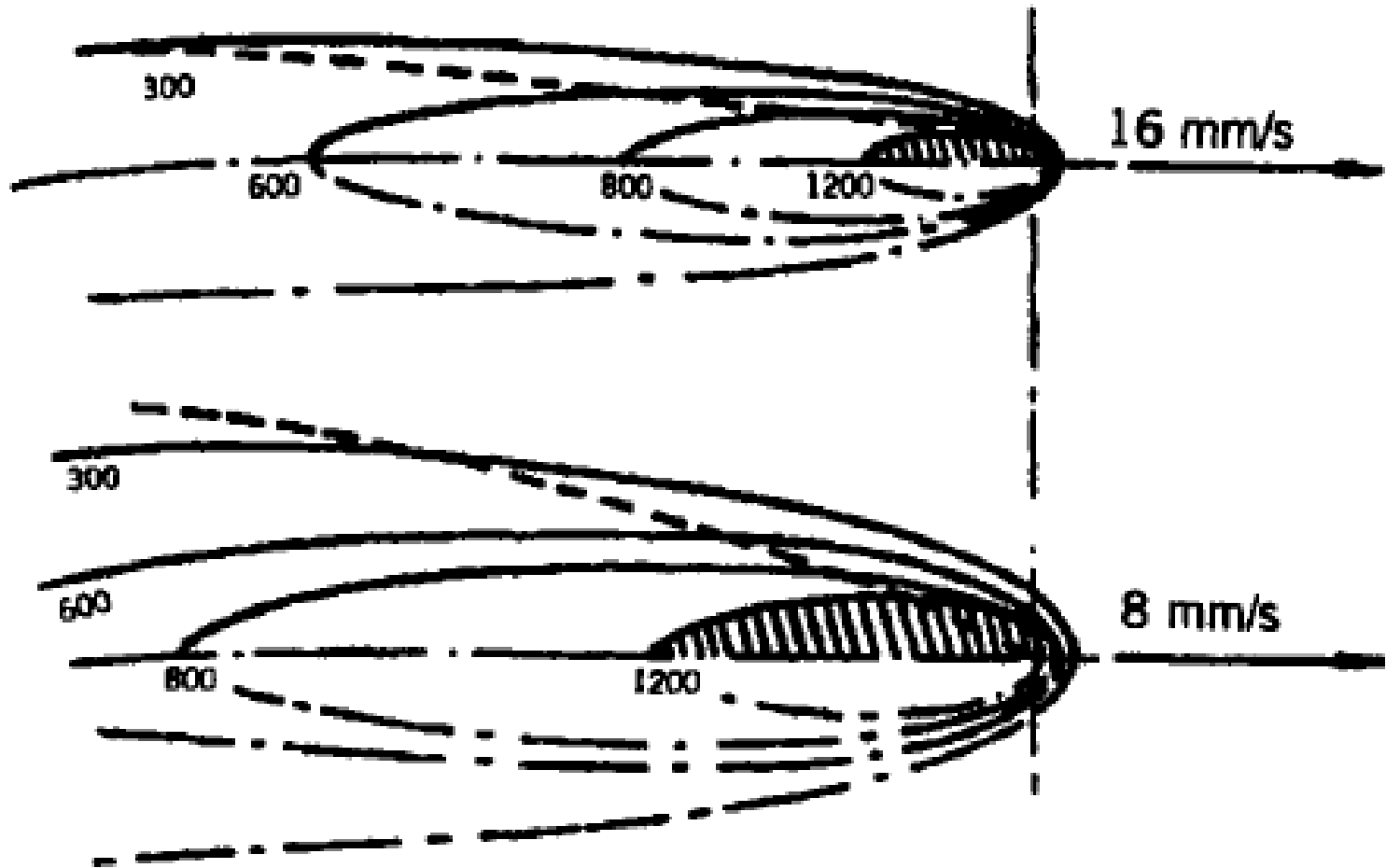
- Increasing thermal conductivity
 - tends to cause deposited heat to spread
 - Smaller welds for a given heat input and melting temperature
- For a given heat input, the lower the melting point, the larger the weld

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

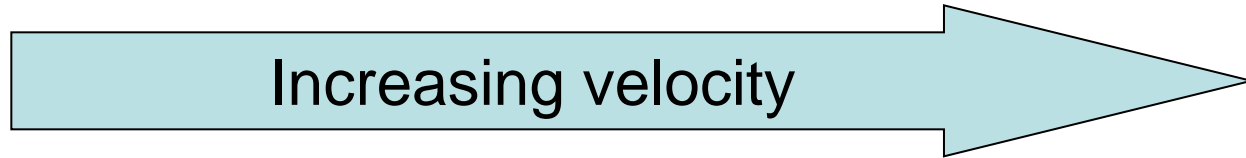


Effect of welding speed



$$q = 3.1 \text{ kJ/s}, d = 3 \text{ mm}$$

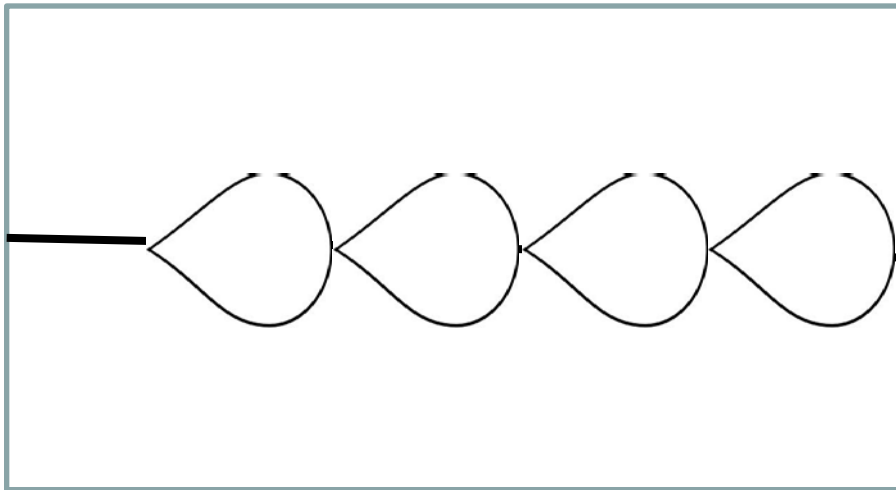
Effect of welding speed on Shape of Fusion/HAZ



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

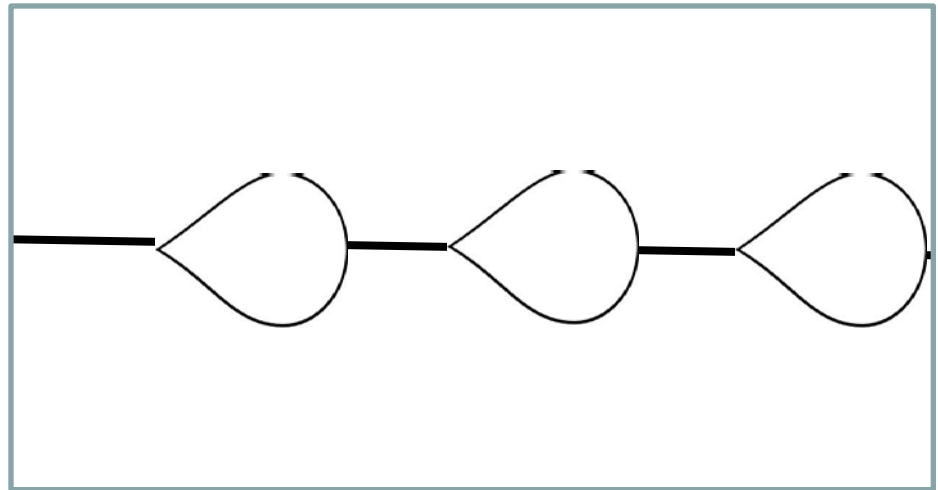
Tear drop formation at very high velocity

Continuous tear drops



Weld direction

Detached tear drops at very high velocity



Weld direction

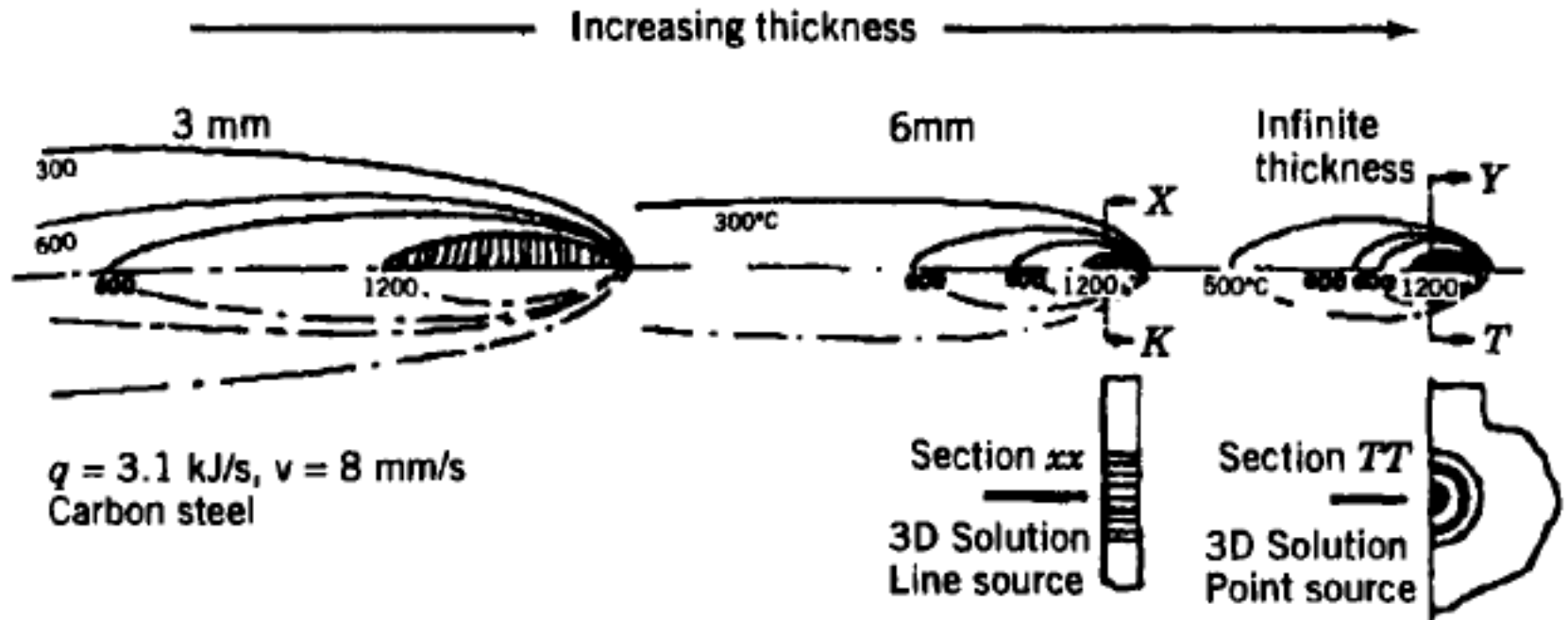
Effect of welding speed

- 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 tear drop shape forms, with a tail at the trailing end of the pool.

Effect of welding speed

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

Effect 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 (T_m , 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 (T_p) 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_0 = 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 $T_p = T_m$

T_m = melting (or liquidus) temperature of the material being welded (K)

$H_{net} = \eta EI/v$ (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.

$T_m = 1510\text{ C}$, $E = 20\text{ V}$, $I = 200\text{ A}$, Welding speed (v or U) $= 5\text{ mm/s}$, $T_0 = 25\text{ C}$, Arc efficiency $= 0.9$, $\rho C = 0.0044\text{ J/mm}^3\cdot\text{C}$, $t = 5\text{ mm}$, $H_{\text{net}} = 720\text{ J/mm}$

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