Welding Metallurgy

Heat Flow in Welding

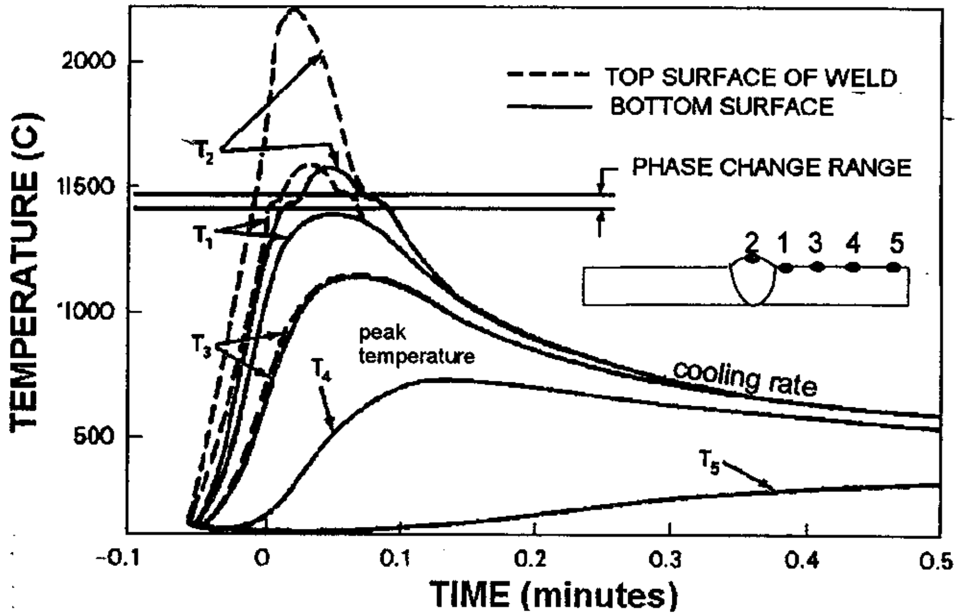
Lecture Scope

- Basic features of welding heat transfer
- Relevant heat flow theory and solutions

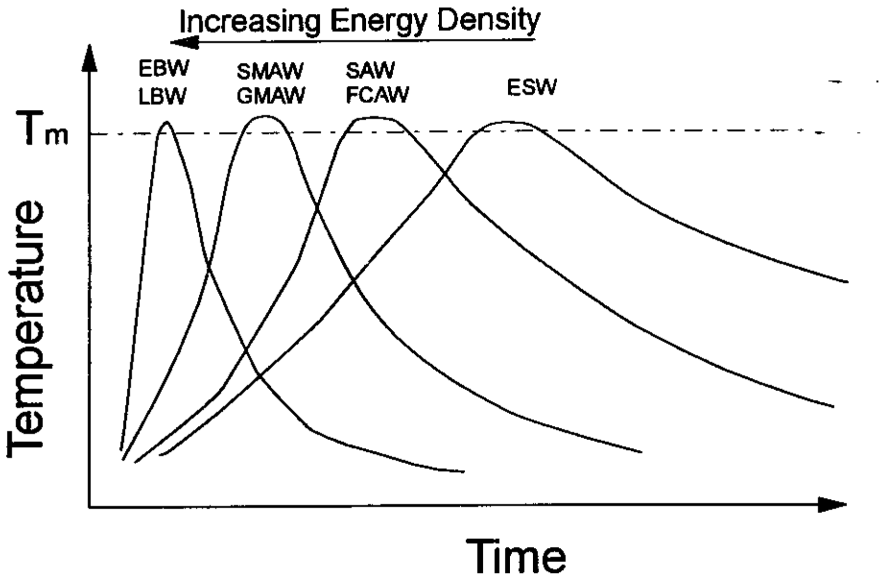
Significance of Thermal Effects

- 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 Heat Affected Zone (HAZ)
  - Width of HAZ
  - Cooling rates in the weld and HAZ

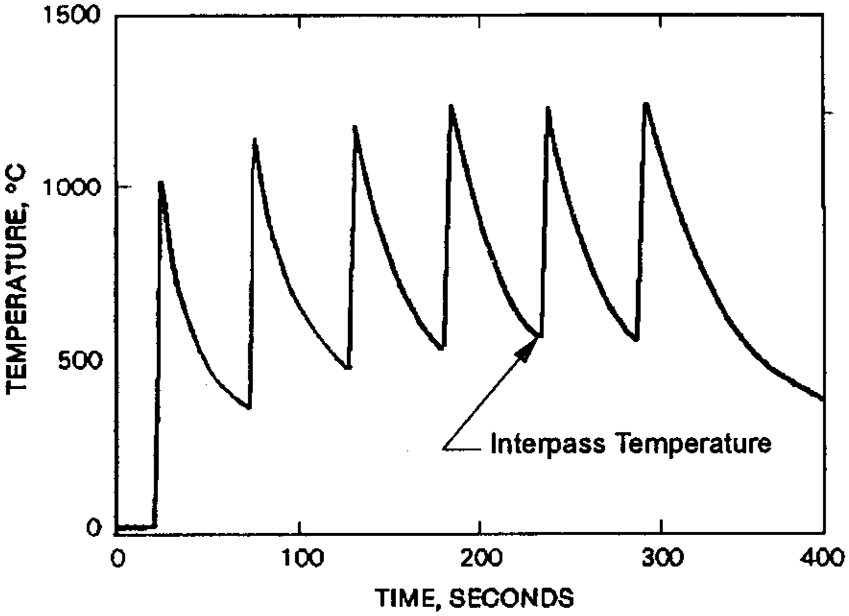
Weld Thermal Cycle



Thermal Cycles Due to Different Welding Processes



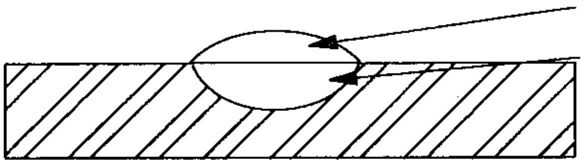
Multiple Pass Weld Cycles



Heat Balance

- The power delivered to the work from the arc is $q_a = \eta VI$
- Thermal energy is dissipated by conduction in the solid and by convection and radiation to the surroundings
- Conduction in the solid predominates

Weld Area



A1 = Filler Area

A2 = Area of base metal melted

Weld Area Aw = A1 + A2

- Heat input must be sufficient to overcome losses and to supply the energy needed for melting
- The minimum power required for melting is HA_wv where H is the energy required to melt unit volume of metal
- Melting efficiency $f_2 = (HA_w v)/(\eta VI)$
- Higher energy densities reduce heat losses and give greater melting efficiency

Weld Area

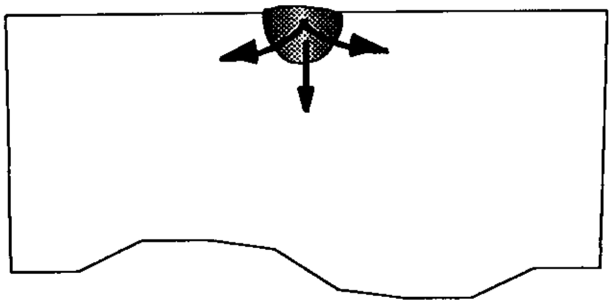
- Assume arc efficiency, η, and the melting efficiency f_2 do not vary greatly for a given welding process.
- From the previous equations it can be seen that the cross section of a single weld bead is roughly proportional to the energy input, i.e.
  - $A_w = f_2 \eta VI/Hv$
- For example, consider an arc weld on steel made under the following conditions:
  - $V=10V$,
  - $I=200A$,
  - $v=5$ mm/s,
  - $\eta = .9$,
  - $f2 = .3$,
  - $H = 10$ J/mm^3
- Then $A_w = 11.3$ mm

Heat Flow Theory

- Heat flow in the solid is determined by:
  - workpiece thickness
  - edge, end effects
  - thermal conductivity and specific heat
  - heat source distribution
  - convection in the weld pool
  - latent heat absorption and release

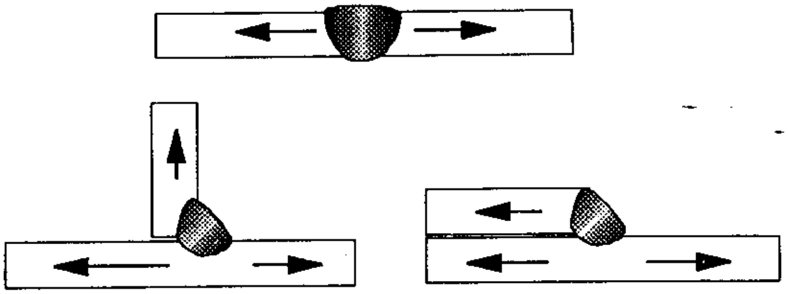
Effect of Relative Plate Thickness

(a) Thin Plate: 2-D Heat Flow

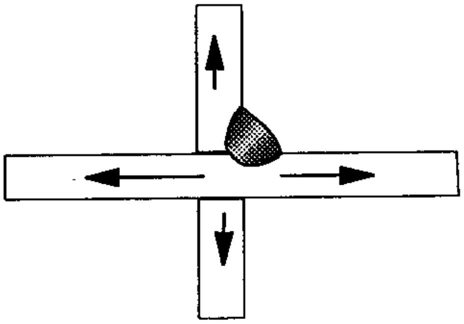


(b) Thick Plate: 3D Heat Flow

Effect of Heat Flow Paths



Multiple paths increase effective plate thickness



Heat Flow Solutions

- Computer numerical modelling techniques are now capable of solving weld thermo-mechanical problems with a high degree of accuracy
- Traditional analytical solutions for heat conduction are still useful and give insights on the effects of welding variables

Heat Flow Equation

With simplifying assumptions, steady state heat conduction in a moving solid may be described by the following equation:

$$\alpha \nabla^2 T - v \frac{\partial T}{\partial x} = 0 \qquad (1)$$

where

$\alpha = \kappa / \rho C_p$

α = thermal diffusivity

κ = thermal conductivity

ρ = density

C_p = specific heat

Solutions to Heat Flow Equation

Solution of Equation (1) gives the following expressions for the temperature field round a "quasi-stationary" heat source

(a) Thin Plate 2D Heat Flow

$$T = \frac{q}{2\pi\kappa r} e^{-v(r-x)/2\alpha} \qquad (2)$$

(b) Thick Plate 3D Heat Flow

$$T = \frac{q}{2\pi\kappa} e^{vx/2\alpha} K_0\left(\frac{vr}{2\alpha}\right) \qquad (3)$$

K_0 is Bessel function (tabulated) and $r = \sqrt{x^2 + y^2 + z^2}$

Peak Temperature

The following equation applies to thin plate (2D)

$$\frac{1}{T_p - T_0} = \frac{\sqrt{2\pi e}\rho c_p h y v}{q} + \frac{1}{T_m - T_0} \qquad (4)$$

T_p = peak temperature
T_0 = initial plate temperature
T_m = melting temperature
e = Base of natural logarithms (2.718)
h = plate thickness
y = distance from fusion line

Cooling Rates

Expressions for cooling rates are obtained by differentiating the previous equations with respect to time. For points on the weld centreline:

(a) Thick Plate

$$\frac{\partial T}{\partial t} = \frac{2\pi\kappa v}{q}(T - T_0) \qquad (5)$$

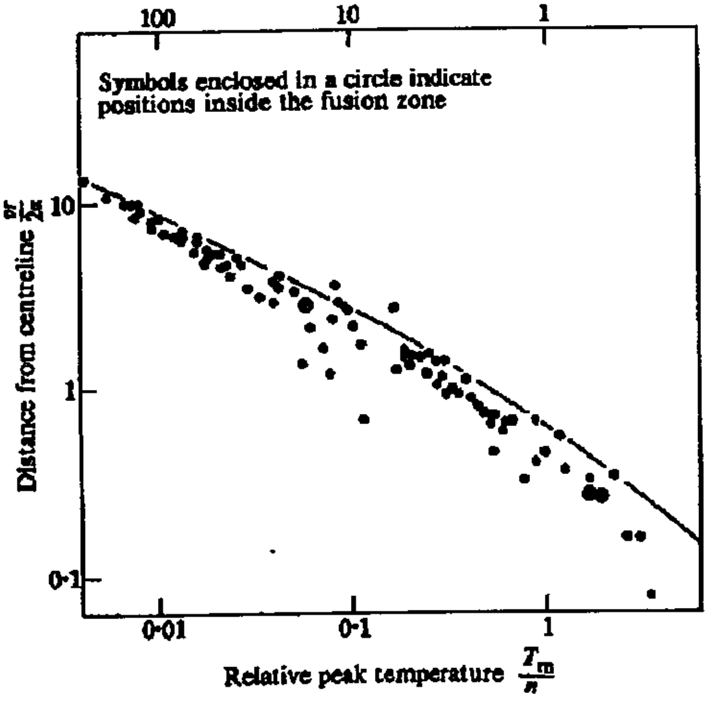
(b) Thin Plate

$$\frac{\partial T}{\partial t} = \frac{2\pi\kappa\rho c_p h^2 v^2}{q^2}(T - T_0)^3 \qquad (6)$$

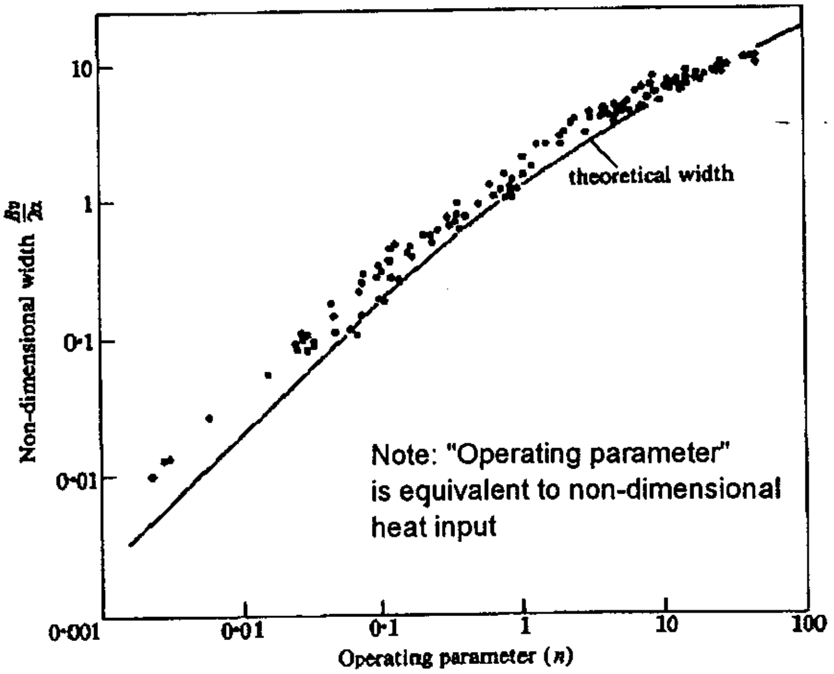
Effects of Welding Variables

- These equations show that weld bead area, peak temperatures, weld width, and cooling rates are determined by:
  - Heat input per unit length ***q/v,*** and
  - Initial plate temperature T_0, or preheat temperature
- The effects of increased heat input and preheat temperature are to:
  - increase peak temperatures at points outside the fusion boundary
  - increase weld bead area
  - decrease cooling rates.

Peak Temperatures

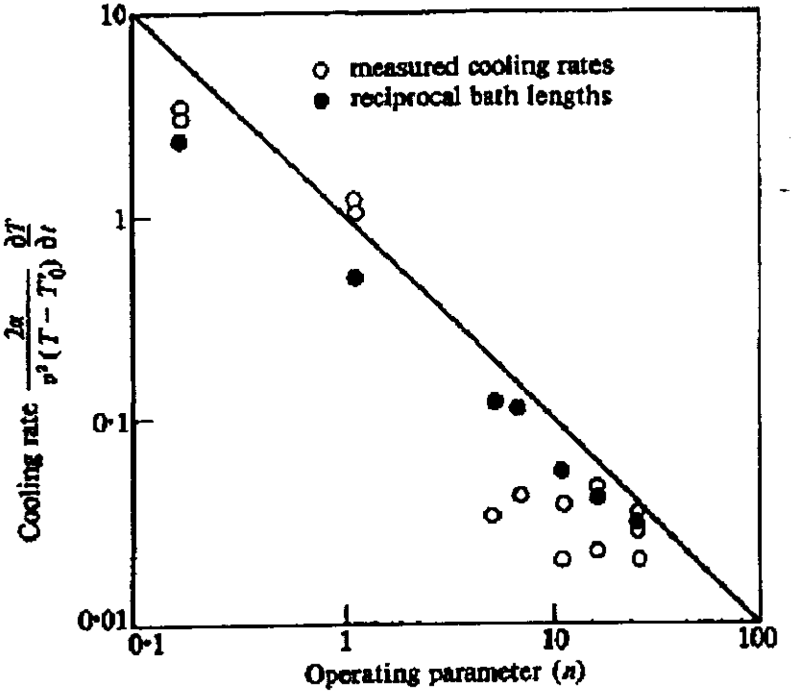


Weld width

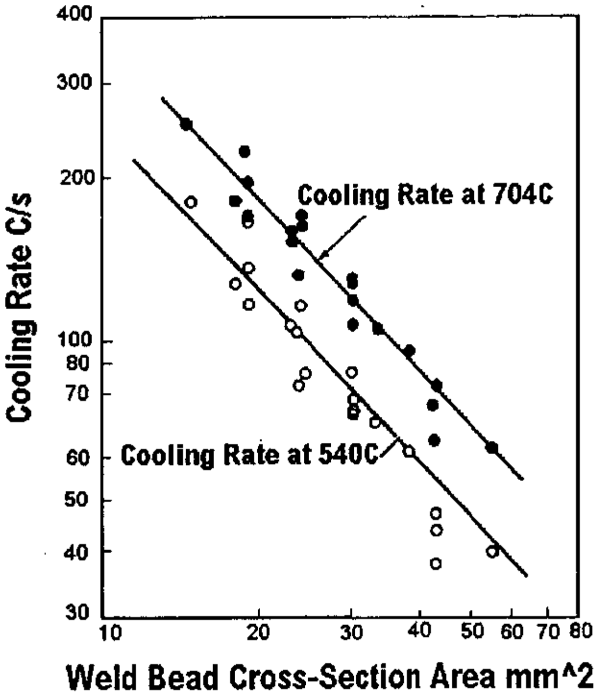


Note: "Operating parameter" is equivalent to non-dimensional heat input

Cooling Rates



Cooling Rates & Weld Area



Example

Consider a full-penetration arc weld pass on a steel plate under the following conditions:

Plate thickness	10 mm	Melting temperature	1510 C
Welding current	200 A	Energy for melting	10 J/mm^3
Voltage	20 V	Thermal conductivity	.028 W/mm/K
Travel Speed	5mm/s	Density	7800 kg/m^3
Arc efficiency	0.9	Specific heat	440 J/kg/K
Melting Efficiency	0.3	Initial temperature	25 C

Estimate the:

1. Heat input per unit length
2. Weld area
3. Width of HAZ > 730 C
4. Centreline cooling rate at 550 C

Answers

1. Heat input, ***q*** $= \eta VI/v$
   $= 0.9*20*200/5$
   $= 720$ J/mm
2. Weld area, ***Aw*** $= f_2\ \eta(VI)/(Hv)$
   $= 0.3*720/10$
   $= 21.6$ mm^2
3. Width of HAZ
   Taking 730 C as the peak temperature in Equation 4 gives the width of the HAZ from the fusion line as 5.9 mm

4. From Equation 6 for 2D heat flow , the cooling rate at 550 C is 16.8 C/s