Welding Design

Module 4

Module 4 – Welding Design

- 4A – Heat Flow
- 4B – Residual Stress and Distortion
- 4C – Fracture and Fatigue
- 4D – Joint Design
- 4E – Welding Symbols
- 4F – Mechanical Testing

Module 4 Learning Objectives

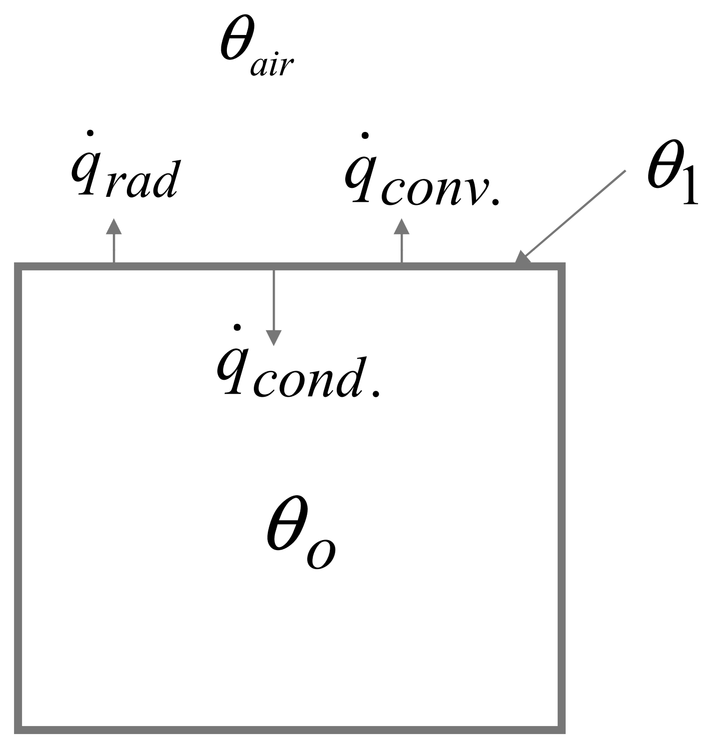
- Basic understanding of heat flow, heat flow with moving heat sources, estimation of cooling rates and HAZ
- Basic understanding of residual stress and distortion principles and mitigation methods
- Understanding of weld design, weld joints and welding symbols
- Basic understanding and purpose of different types of destructive tests

Heat Flow

Module 4A

Heat Flow

- Conduction
- Radiation
- Convection



Conduction

Fourier's Law of Conduction

Heat flow

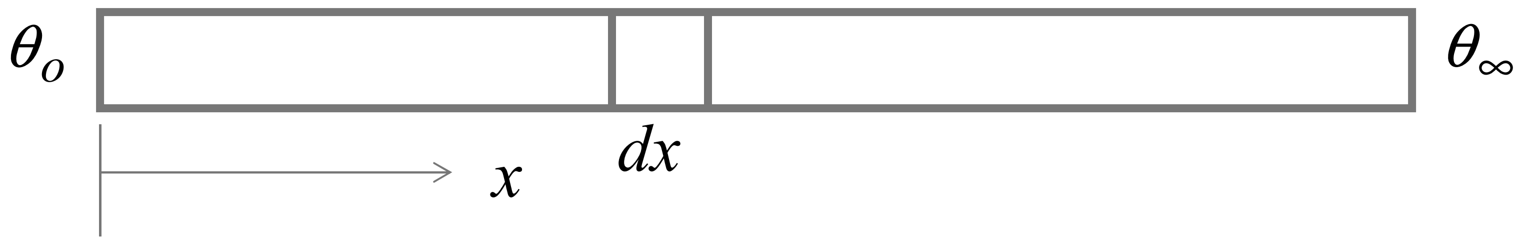
$$\dot{q}_x = \left(\frac{q}{A}\right)_x = -\lambda \frac{d\theta}{dx}$$

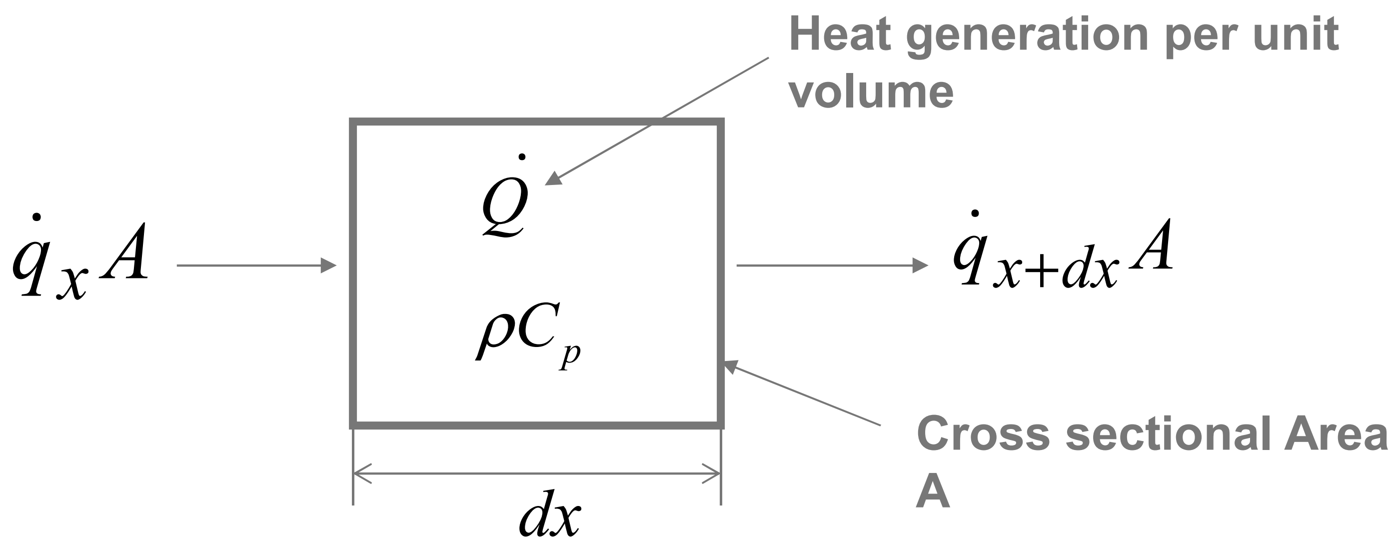
Temp. gradient

Heat flux

Thermal conductivity

1-D Conduction





Conservation of Energy

- Internal energy = energy in – energy out

Specific heat

Density

$$\rho C_p \frac{\partial \theta}{\partial t} A dx = \dot{Q} A dx + \dot{q}_x A - \dot{q}_{x+dx} A$$

Internal Energy change = Internal heat generation + heat in – heat out

Conservation of Energy

But using Taylor series expansion,

$$\dot{q}_{x+dx} = \dot{q}_x + \frac{\partial \dot{q}_x}{\partial \mathrm{x}} dx$$

$$\therefore \quad \rho C_p \frac{\partial \theta}{\partial t} A dx = \dot{Q} A dx + \dot{q}_x A - \dot{q}_x A - \frac{\partial \dot{q}_x}{\partial \mathrm{x}} dx A$$

$$\therefore \quad \rho C_p \frac{\partial \theta}{\partial t} = \dot{Q} - \frac{\partial \dot{q}_x}{\partial \mathrm{x}}$$

Conservation of Energy

<u>Using Fourier's law of conduction</u>

$$\frac{\partial \dot{q}_x}{\partial \mathrm{x}} = \frac{\partial}{\partial \mathrm{x}}\left(-\lambda \frac{\partial \theta}{\partial x}\right)$$

Thus,

$$\rho C_p \frac{\partial \theta}{\partial t} = \dot{Q} + \frac{\partial}{\partial \mathrm{x}}\left(\lambda \frac{\partial \theta}{\partial x}\right)$$

1-D Conduction

To make problem manageable, assume

no internal heat generation

$$\rho C_p \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \theta}{\partial x}\right)$$

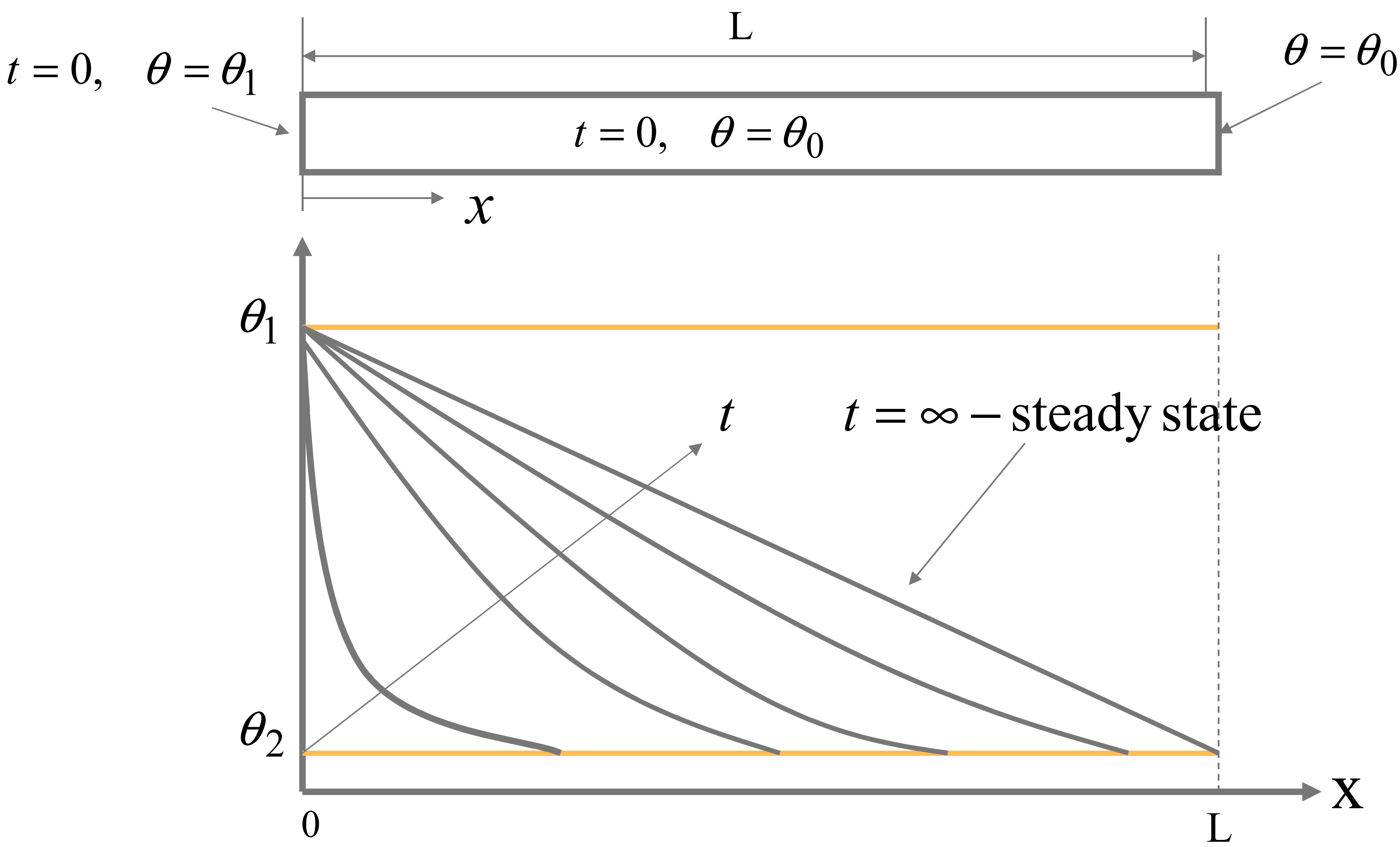
λ is constant, not dependent on x or temperature

$$\rho\, C_p \frac{\partial \theta}{\partial t} = \lambda \; \frac{\partial^2 \theta}{\partial x^2}$$

$$\frac{\partial \theta}{\partial t} = \frac{\lambda}{\rho C_p}\left(\frac{\partial^2 \theta}{\partial x^2}\right) = k \frac{\partial^2 \theta}{\partial x^2}$$

κ=thermal diffusivity $\left(\frac{\mathrm{m}^2}{\mathrm{sec}}\right)$

Conservation of Energy (Con't)



1-D Conduction
Steady State without Internal Heat Generation

$$\frac{\partial^2\theta}{\partial x^2} = \cancelto{0}{\dot{Q}} + \cancelto{0}{\frac{1}{\kappa}\frac{\partial\theta}{\partial t}}$$

Giving,

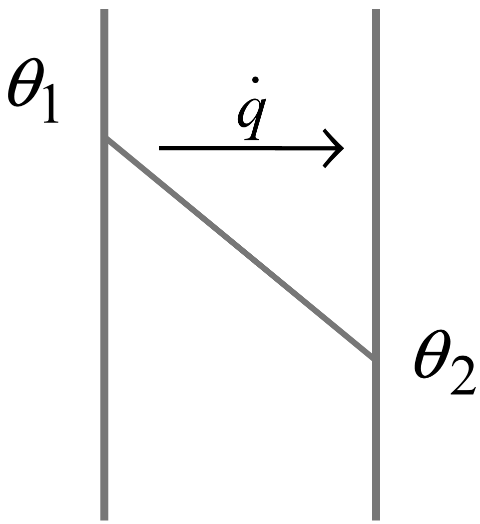
$$\frac{\partial^2\theta}{\partial x^2} = 0$$

General Solution

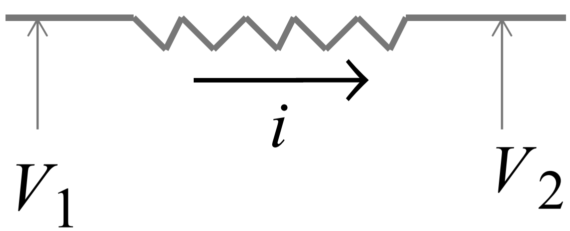
$$\frac{\partial\theta}{\partial x} = c_1$$

$$\boxed{\theta = c_1 x + c_2}$$

Concept of Thermal Resistance



$$R_{thermal} = \frac{\theta_1 - \theta_2}{\dot{q}}$$



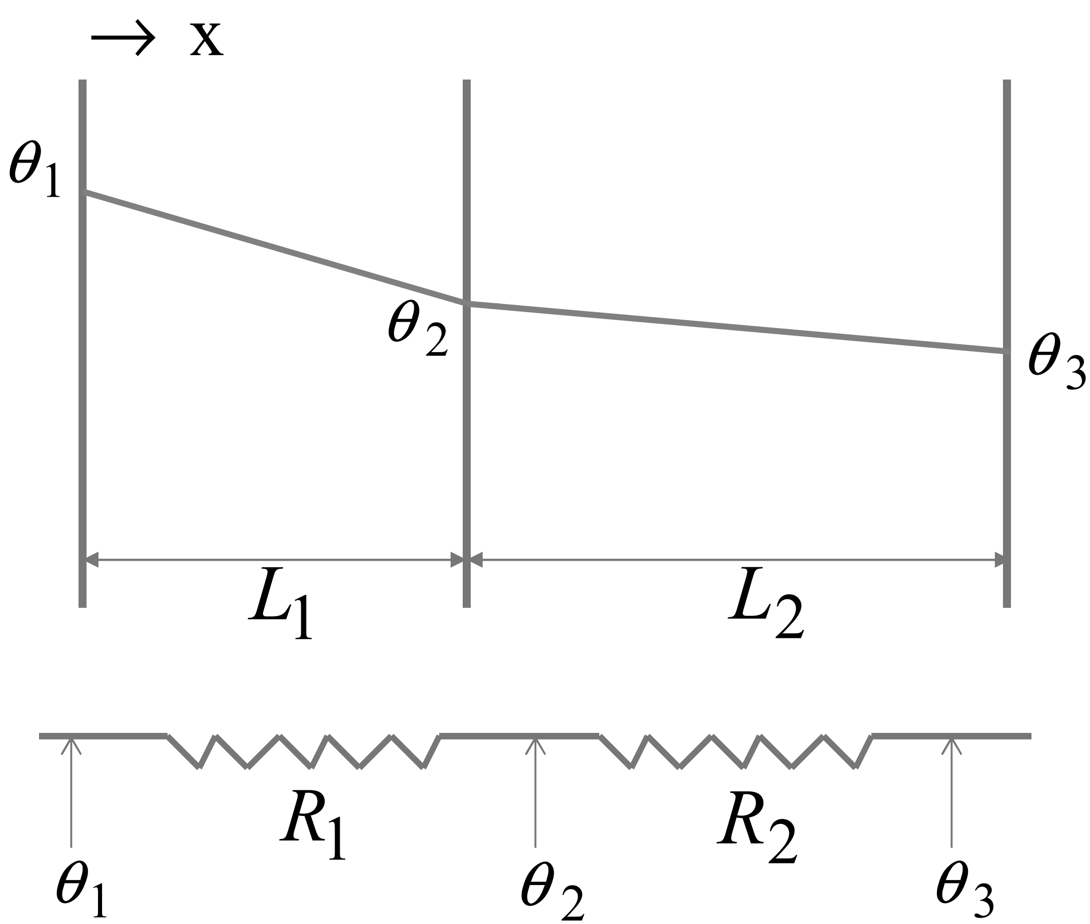
$$R_{electrical} = \frac{V_1 - V_2}{i}$$

Concept of Thermal Resistance

but $$\dot{q} = -\lambda\ A\frac{\partial\theta}{\partial x} = -\lambda\ A\frac{\theta_2 - \theta_1}{L} = \lambda\ A\frac{\theta_1 - \theta_2}{L}$$

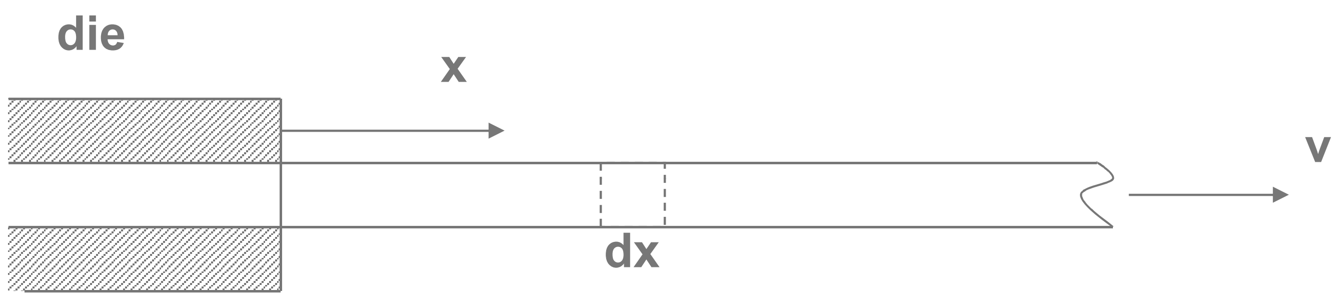
$$\mathrm{R}_{\mathrm{thermal}} = \frac{\theta_1 - \theta_2}{\lambda\ A\dfrac{\theta_1 - \theta_2}{L}} = \frac{L}{\lambda\ A}$$

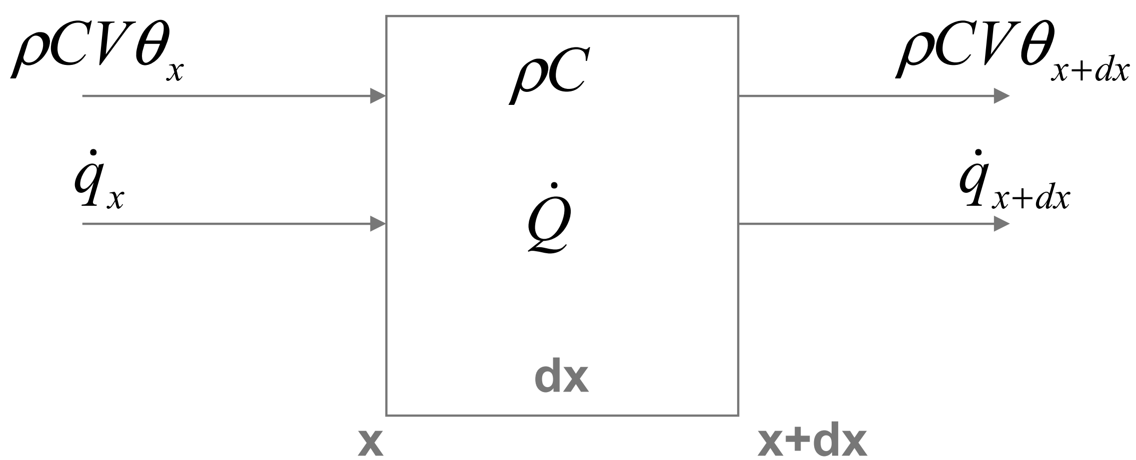
Composite Walls



1-D Conduction with Mass Movement

- Consider an extrusion process





1-D Conduction with Mass Movement

Applying conservation of energy to the control volume

$$\rho C \frac{\partial \theta}{\partial t} A dx = \dot{Q} A dx + \dot{q}_x A - \dot{q}_{x+dx} A + \rho C V \theta_x A - \rho C V \theta_{x+dx} A$$

Using Taylor series expansion and simplifying

$$\rho C \frac{\partial \theta}{\partial t} = \dot{Q} - \frac{\partial \dot{q}_x}{\partial x} - \rho C V \frac{\partial \theta}{\partial x}$$

Using Fourier's Law of Conduction

$$\rho C \frac{\partial \theta}{\partial t} = \dot{Q} + \lambda \frac{\partial^2 \theta}{\partial x^2} - \rho C V \frac{\partial \theta}{\partial x}$$

1-D Conduction with Mass Movement

In this case if you look at some location x with respect to time, the temperature at that location will remain constant (assuming we are past the transients from starting the process). Therefore, we can model this as a Quasi-Steady problem.

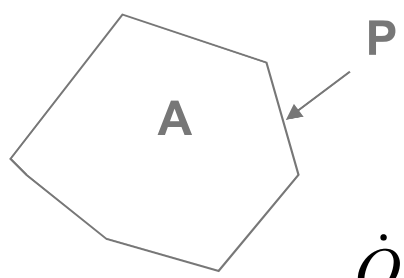
$$\rho C \underbrace{\frac{\partial \theta}{\partial t}}_{0} = \dot{Q} + \lambda \frac{\partial^2 \theta}{\partial x^2} - \rho C V \frac{\partial \theta}{\partial x}$$

$$0 = \dot{Q} + \lambda \frac{\partial^2 \theta}{\partial x^2} - \rho C V \frac{\partial \theta}{\partial x}$$

1-D Conduction with Mass Movement

If the cross section of the rod is small, we can assume that the temperature is constant at every cross section. In that case we can consider the heat loss due to convection as a negative internal heat generation rate.

Consider some cross section of area A and perimeter P



$$\dot{Q} A dx = -hPdx(\theta - \theta_\infty) \Rightarrow \dot{Q} = -\frac{hP}{A}(\theta - \theta_\infty)$$

1-D Conduction with Mass Movement

Therefore,

$$\lambda \frac{\partial^2 \theta}{\partial x^2} - \rho C V \frac{\partial \theta}{\partial x} - \frac{hP}{A}(\theta - \theta_\infty) = 0$$

Let

$$\theta' = (\theta - \theta_\infty), \quad \frac{\partial \theta'}{\partial x} = \frac{\partial \theta}{\partial x}, \text{ and } \quad \frac{\partial^2 \theta'}{\partial x^2} = \frac{\partial^2 \theta}{\partial x^2}$$

Giving,

$$\frac{\partial^2 \theta'}{\partial x^2} - \frac{V}{\kappa}\frac{\partial \theta'}{\partial x} - \frac{hP}{\lambda A}\theta' = 0$$

Solving,

$$\theta'(x) = C_1 \exp\left(\left(\frac{V}{2\kappa} - \sqrt{\left(\frac{V}{2\kappa}\right)^2 + \frac{hP}{\lambda A}}\right)x\right) + C_2 \exp\left(\left(\frac{V}{2\kappa} + \sqrt{\left(\frac{V}{2\kappa}\right)^2 + \frac{hP}{\lambda A}}\right)x\right)$$

1-D Conduction with Mass Movement

Applying the boundary conditions.

As $x \rightarrow \infty$ **then** $\theta' = 0$

$$\theta'(x=\infty) = C_1 \exp\left(\left(\frac{V}{2\kappa} - \sqrt{\left(\frac{V}{2\kappa}\right)^2 + \frac{hP}{\lambda A}}\right)\infty\right) + C_2 \exp\left(\left(\frac{V}{2\kappa} + \sqrt{\left(\frac{V}{2\kappa}\right)^2 + \frac{hP}{\lambda A}}\right)\infty\right)$$

(first exponent $\rightarrow 0$; second exponent $\rightarrow \infty$)

Since the second term goes to infinity than $C_2 = 0$

1-D Conduction with Mass Movement

At $x = 0$ then $\theta' = \left(\theta_{die} - \theta_{\infty}\right) = \theta'_{die}$

1

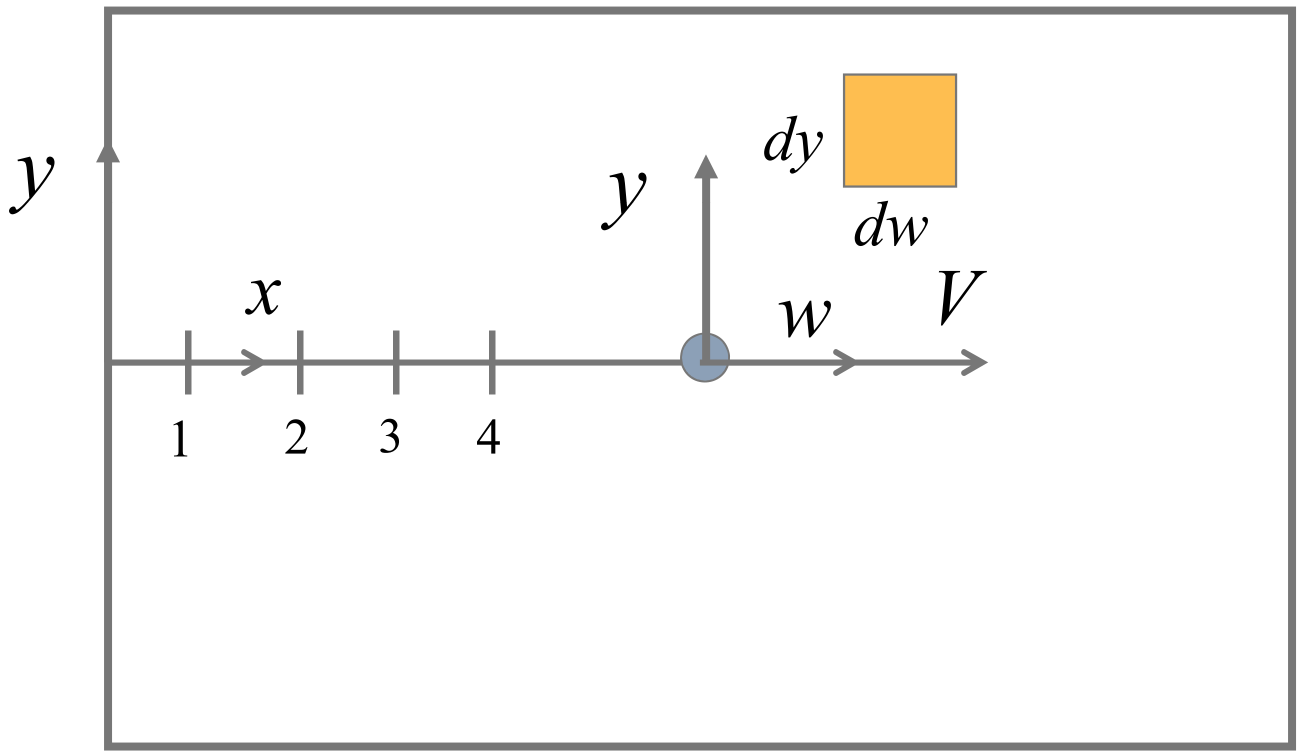
$$\theta'(x=0) = \theta'_{die} = C_1 \exp\left(\left(\frac{V}{2\kappa} - \sqrt{\left(\frac{V}{2\kappa}\right)^2 + \frac{hP}{\lambda A}}\right)0\right)$$

Therefore, $C_1 = \theta'_{die}$ giving,

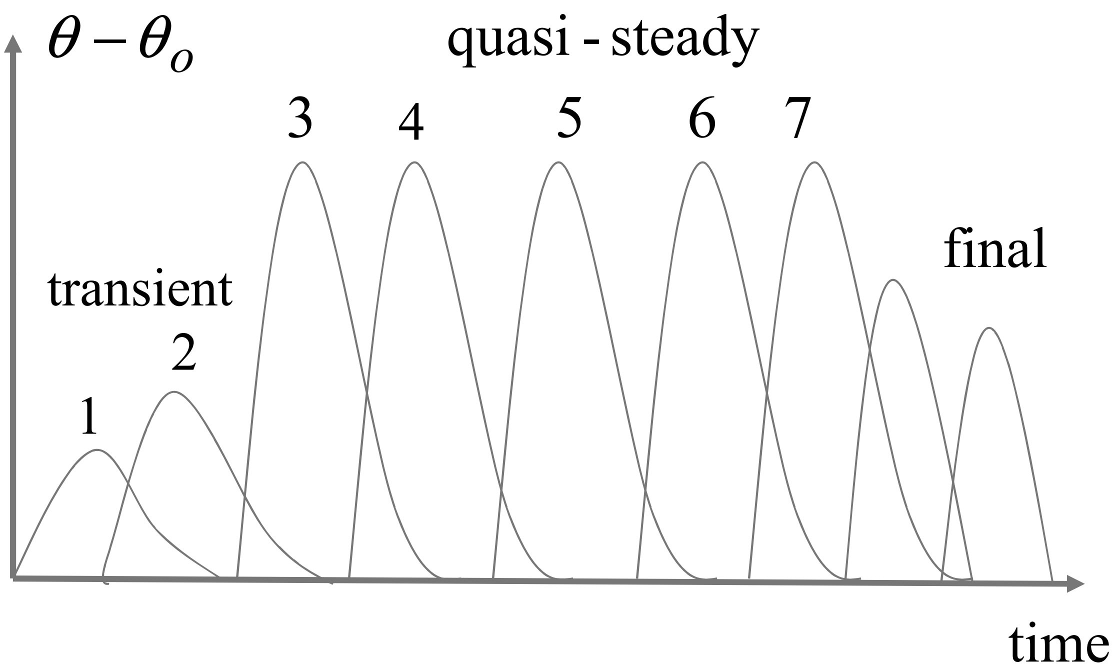
$$\theta'(x) = \theta'_{die} \exp\left(\left(\frac{V}{2\kappa} - \sqrt{\left(\frac{V}{2\kappa}\right)^2 + \frac{hP}{\lambda A}}\right)x\right)$$

Heat Flow with Moving Coordinate System

- Consider a very large and very thin plate – thickness (h)



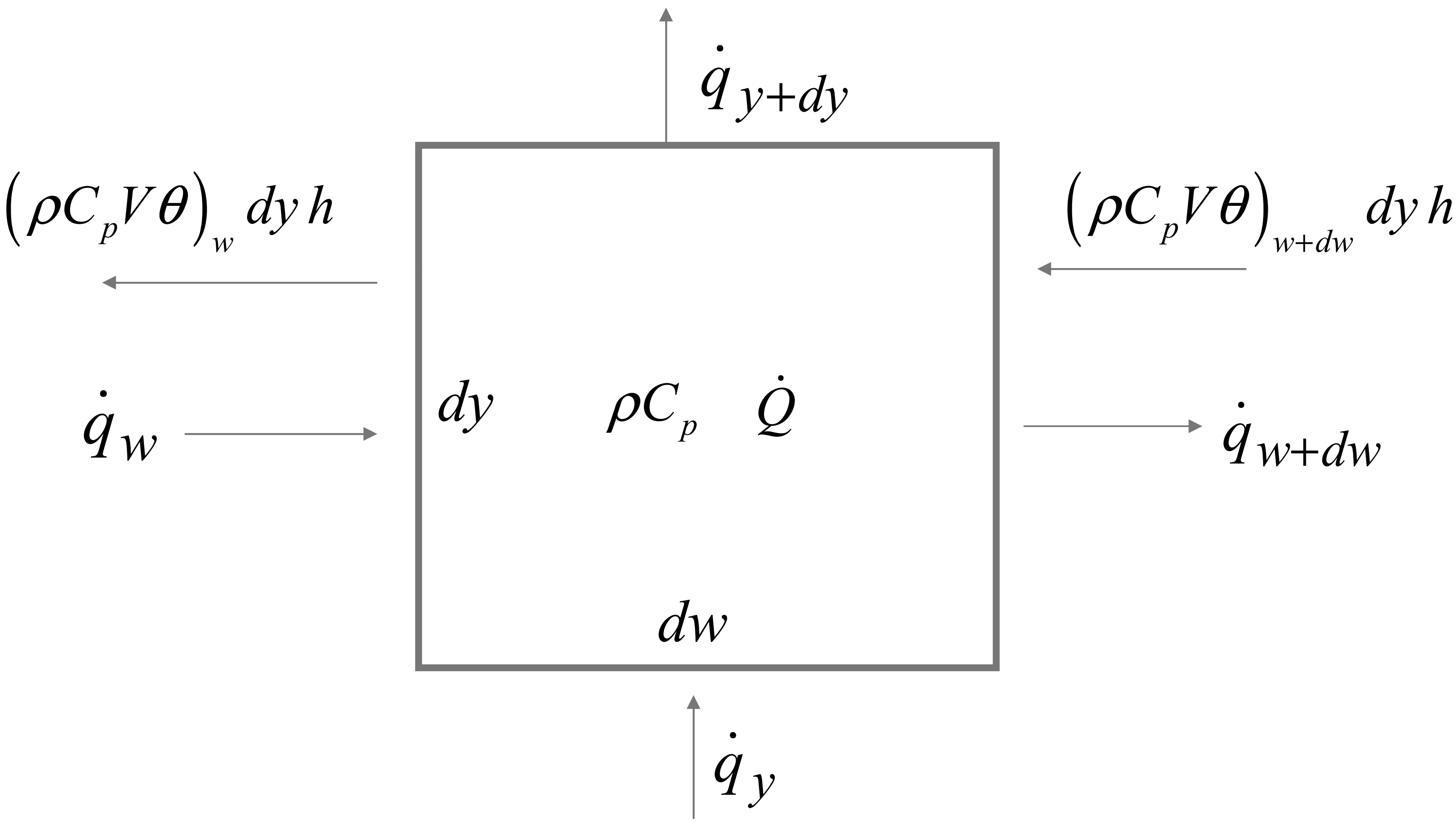
Heat Flow with Moving Coordinate System



Moving with the welding arc in quasi-steady region, the temperature is constant with respect to time. Form a new moving coordinate system:

$$w = x - Vt$$

Heat Flow with Moving Coordinate System



Heat Flow with Moving Coordinate System

Balance heat flow in y direction,

$$\left(\dot{q}_y - \dot{q}_{y+dy}\right) dw\, h = -\frac{\partial \dot{q}}{\partial y} dy\, dw\, h$$

Balance heat flow in w direction,

$$\left(\dot{q}_w - \dot{q}_{w+dw}\right) dy\, h + \left[\left(\rho C_p V \theta\right)_{w+dw} - \left(\rho C_p V \theta\right)_w\right] dy\, h =$$

$$-\frac{\partial \dot{q}}{\partial w} dw\, dy\, h + \frac{\partial}{\partial w}\left(\rho C_p V \theta\right) dw\, dy\, h$$

Heat Flow with Moving Coordinate System

Conservation of energy for control volume

$$\rho C_p \frac{\partial \theta}{\partial t} \cancel{dydwh} = \dot{Q} - \frac{\partial \dot{q}}{\partial y} \cancel{dydwh} - \frac{\partial \dot{q}}{\partial w} \cancel{dwdyh} + \frac{\partial}{\partial w}\left(\rho C_p V \theta\right) \cancel{dwdyh}$$

Using Fourier's Law of Conduction

$$\rho C_p \frac{\partial \theta}{\partial t} = \dot{Q} + \underbrace{\frac{\partial}{\partial w}\left(\lambda \frac{\partial \theta}{\partial w}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial \theta}{\partial y}\right)}_{\text{Conduction}} + \underbrace{\frac{\partial}{\partial w}\left(\rho C_p v \theta_w\right)}_{\text{Convection}}$$

Heat Flow with Moving Coordinate System

Assuming constant properties and constant heat source velocity.

$$\rho C_p \frac{\partial \theta}{\partial t} = \dot{Q} + \lambda \frac{\partial^2 \theta}{\partial w^2} + \lambda \frac{\partial^2 \theta}{\partial y^2} + \rho C_p V \frac{\partial \theta}{\partial w}$$

For quasi-steady,

$$\frac{\partial^2 \theta}{\partial w^2} + \frac{\partial^2 \theta}{\partial y^2} = -\frac{V}{k} \frac{\partial \theta}{\partial w}$$

Heat Flow with Moving Coordinate System
3-D Solution for Semi-infinite Plate

Assuming constant properties and constant heat source velocity.

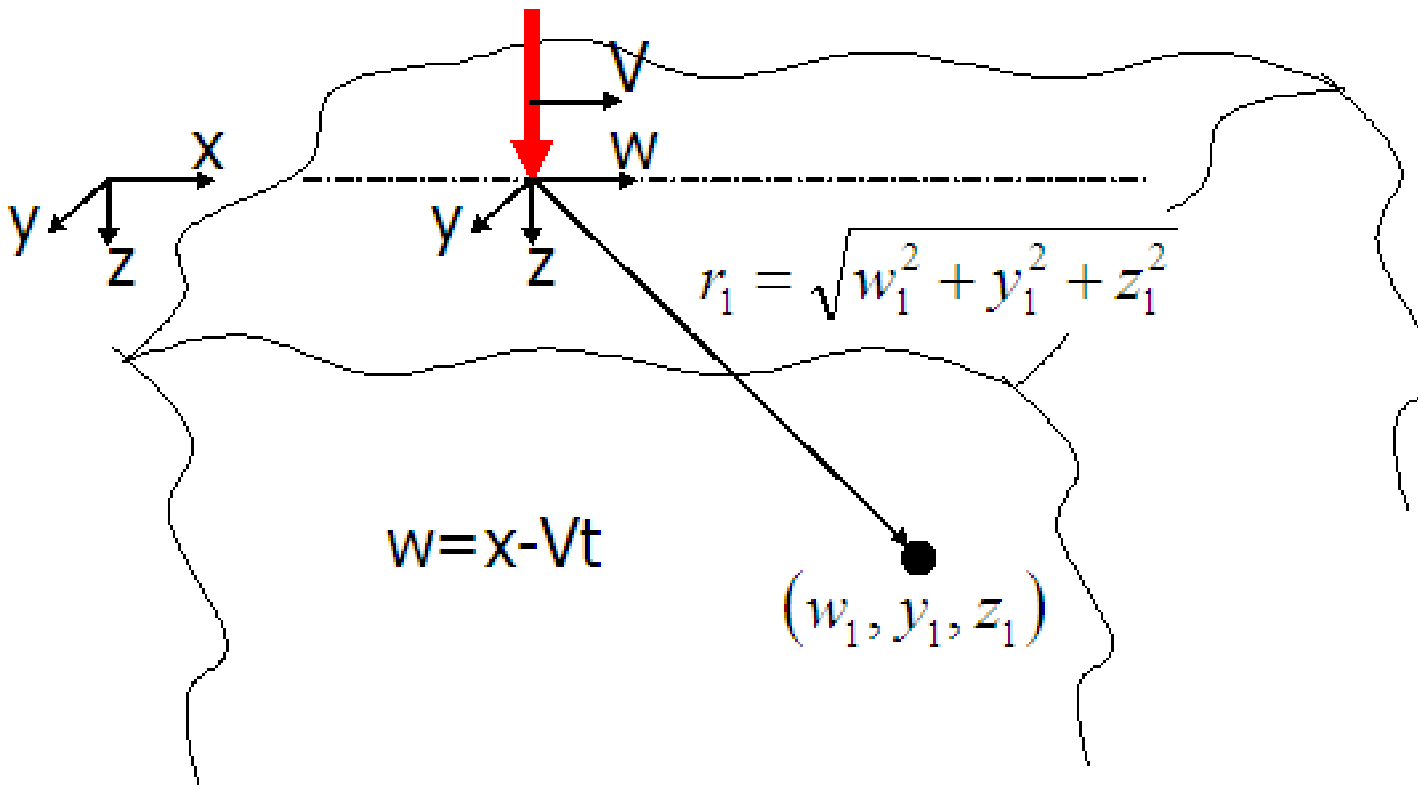
$$\rho C_p \frac{\partial \theta}{\partial t} = \dot{Q} + \lambda \frac{\partial^2 \theta}{\partial w^2} + \lambda \frac{\partial^2 \theta}{\partial y^2} + \lambda \frac{\partial^2 \theta}{\partial z^2} + \rho C_p V \frac{\partial \theta}{\partial w}$$

For quasi-steady,

$$\frac{\partial^2 \theta}{\partial w^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} = -\frac{V}{k} \frac{\partial \theta}{\partial w}$$

Heat Flow with Moving Coordinate System 3-D Solution for Semi-infinite Plate

Define $r = \sqrt{w^2 + y^2 + z^2}$



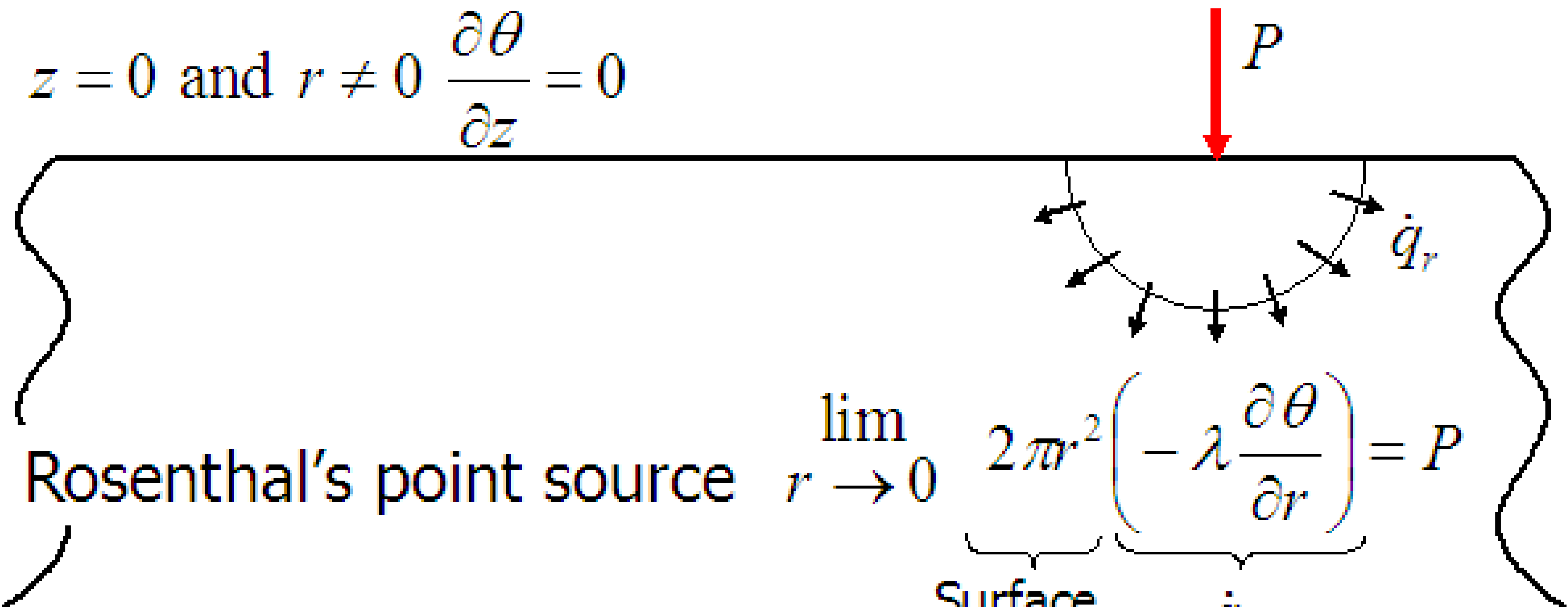
Heat Flow with Moving Coordinate System 3-D Solution for Semi-infinite Plate

Boundary conditions

Very far from the heat source. $\lim_{r \to \infty} \frac{\partial \theta}{\partial r} = 0$

No heat losses from top surface

$z = 0 \text{ and } r \neq 0 \quad \frac{\partial \theta}{\partial z} = 0$



Rosenthal's point source $\lim_{r \to 0} \underbrace{2\pi r^2}_{\text{Surface area of hemisphere}} \underbrace{\left(-\lambda \frac{\partial \theta}{\partial r} \right)}_{\dot{q}_r} = P$

Heat Flow with Moving Coordinate System
3-D Solution for Semi-infinite Plate

General solution:

$$\theta - \theta_0 = \frac{P}{2\pi\lambda r} \exp\left(-\frac{V}{2\kappa}(w + r) \right)$$

For arc welding $P = fEI$

Where, P is input power

f is arc efficiency

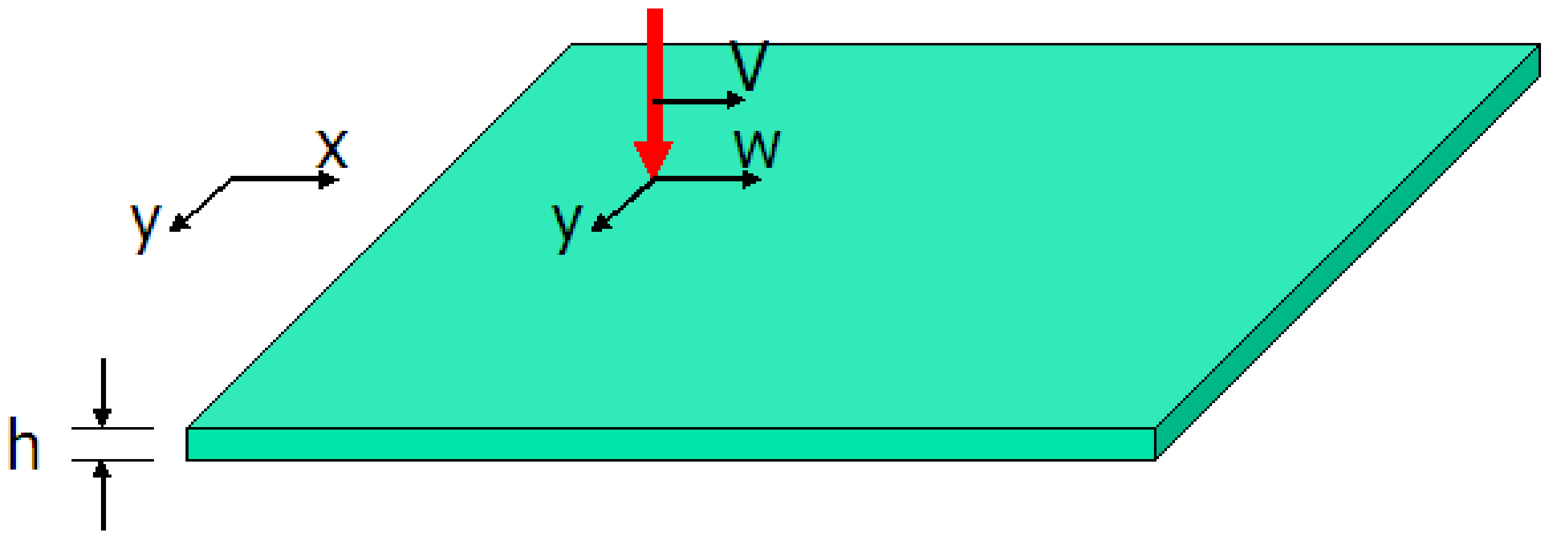
E is arc voltage

I is arc current

Heat Flow with Moving Coordinate System
2-D Solution for Thin Plate

Consider a very thin plate

$$r = \sqrt{w^2 + y^2}$$



The temperature is the same through the thickness
Of the plate.

Heat Flow with Moving Coordinate System 2-D Solution for Thin Plate

General solution:

$$\theta - \theta_0 = \frac{P}{2\pi\lambda r} \exp\left(-\frac{Vw}{2\kappa}\right) K_0\left(\frac{Vr}{2\kappa}\right)$$

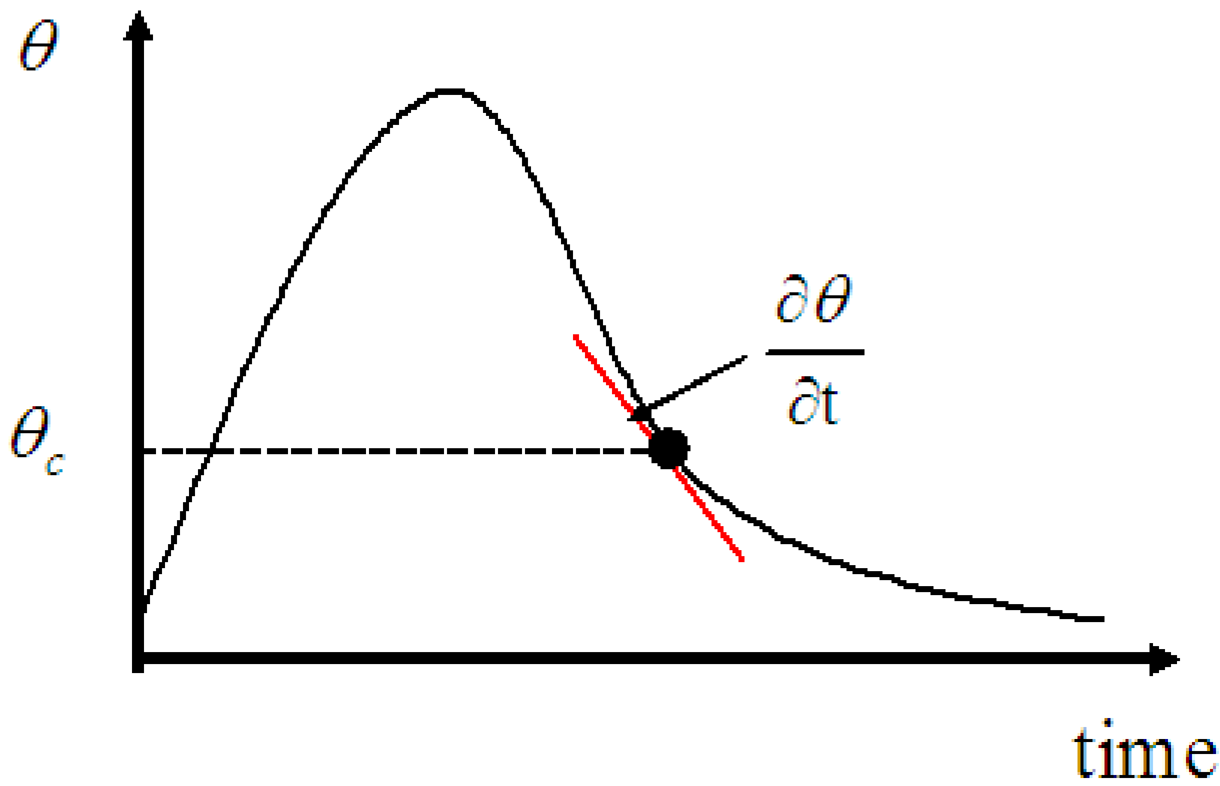
$K_0(z)$ is the modified Bessel function of the second kind and zero order.

$$K_0(z) = \int_1^\infty \frac{\exp(-zt)}{\sqrt{t^2 - 1}} dt$$

For z large $K_0(z) \cong \sqrt{\frac{\pi}{2z}} \exp(-z)$

Cooling Rate Equation

Need to know location and temp for which we need Cooling rate (slope).



Cooling Rate Equation

- Consider the semi-infinite plate solution:

$$\theta - \theta_o = \frac{P}{2\pi\lambda r}\exp\left(-\frac{V(w+r)}{2\kappa}\right)$$

Notice that θ is not a function of time in the Eq.

But w is a function of time $w = x - Vt$

Therefore, we can use the chain rule $\frac{\partial\theta}{\partial t} = \frac{\partial\theta}{\partial w}\cdot\frac{\partial w}{\partial t}$

Where $\frac{\partial w}{\partial t} = -V$ Giving, $\frac{\partial\theta}{\partial t} = -V\frac{\partial\theta}{\partial w}$

Cooling Rate Equation

Consider the semi-infinite plate solution:

$$\theta - \theta_o = \frac{P}{2\pi\lambda r}\exp\left(-\frac{V(w+r)}{2\kappa}\right)$$

Notice that θ is not a function of time in the Eq.

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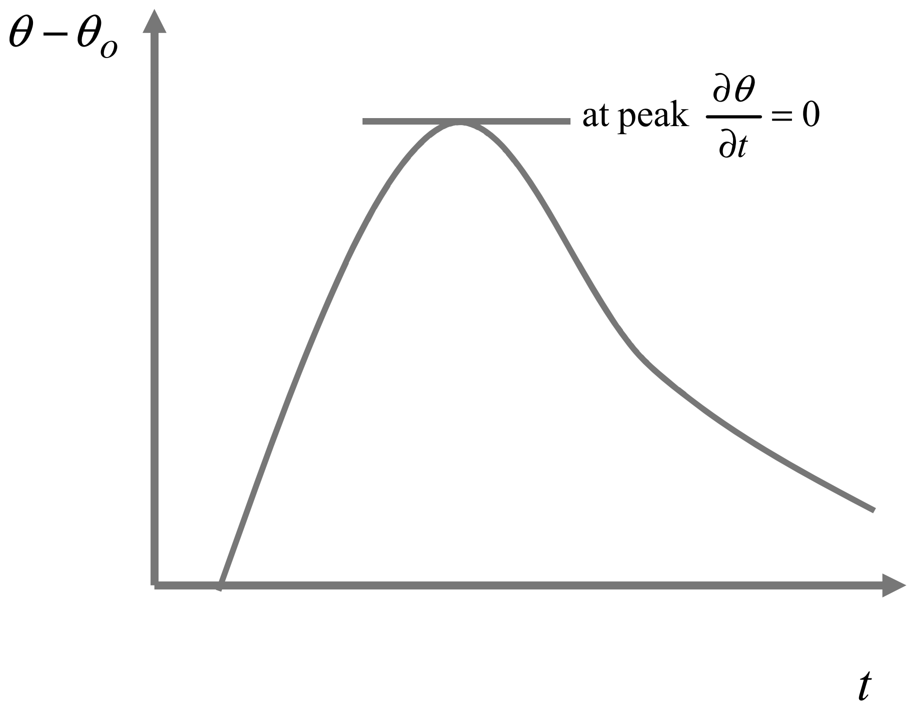
Therefore, we can use the chain rule $\frac{\partial\theta}{\partial t} = \frac{\partial\theta}{\partial w}\cdot\frac{\partial w}{\partial t}$

Where $\frac{\partial w}{\partial t} = -V$ Giving, $\frac{\partial\theta}{\partial t} = -V\frac{\partial\theta}{\partial w}$

$$\frac{\partial\theta}{\partial t} = -V\frac{P}{2\pi\lambda r}\cdot\exp\left(\frac{-V(w+1)}{2\kappa}\right)\cdot\left[-\frac{w}{r^2} - \frac{V}{2\kappa}\left(1+\frac{w}{r}\right)\right]$$

Heat Flow with Moving Coordinate System Peak Temperature Equations

At the peak temperature the slope of the temperature time curve must be zero.



Heat Flow with Moving Coordinate System
Peak Temperature Equations

We previously derived $\dfrac{\partial\theta}{\partial \mathrm{t}}$

$$\frac{\partial\theta}{\partial \mathrm{t}} = -V\,\frac{P}{2\pi\,\lambda\,r}\,e^{-\frac{V}{2\kappa}(w+r)}\left[-\frac{w}{r^2}-\frac{V}{2\kappa}\left(1+\frac{w}{r}\right)\right]=0$$

Therefore, $-\dfrac{w}{r^2}-\dfrac{V}{2\kappa}\left(1+\dfrac{w}{r}\right)=0$

Find relationship between w and r when the point of interest reaches the peak temperature and then use thick plate solution to find peak temp.

$$\theta_{peak}-\theta_o=\frac{P}{2\pi\,\lambda\,r}\,e^{-\frac{V}{2\kappa}(w+r)}$$

Peak Temperature Equations

- We force the eq. to fit experimental results by specifying a known temperature θr at known location rr . Then,

$$\frac{1}{\theta_p - \theta_o} = \frac{\frac{e}{2}\left(\wp c_p \pi \left(r^2 - r_r{}^2\right)\right)}{\frac{\eta_a EI}{V}} + \frac{1}{\theta_r - \theta_o}$$

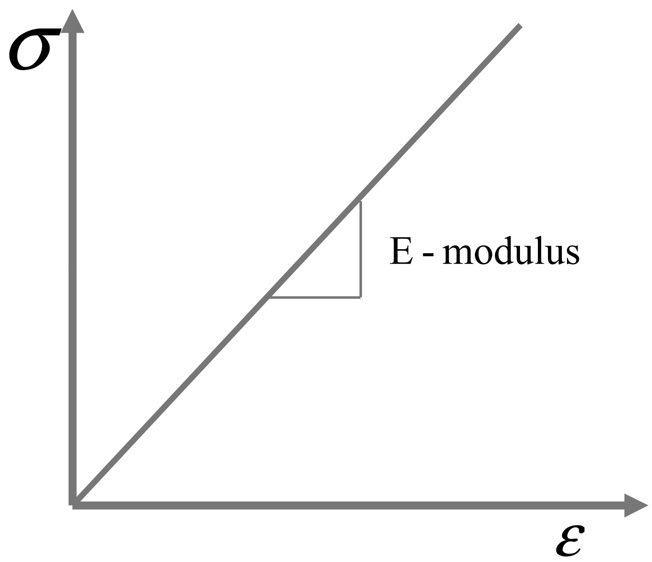
- For example, at fusion boundary θm is the known peak temperature and r=d/2 where (d) is the weld bead with is known location. Then,

$$\frac{1}{\theta_p - \theta_o} = \frac{\frac{e}{2}\left(\wp c_p \pi \left(y^2 - \frac{d}{2}^2\right)\right)}{\frac{\eta_a EI}{V}} + \frac{1}{\theta_m - \theta_o}$$

Residual Stress and Distortion

Module 4B

Linear Elastic Material



Hook's Law Uniaxial Loading $\varepsilon_x = \frac{\sigma_x}{E}$

Poisson's ratio $\varepsilon_y = -\nu \frac{\sigma_x}{E}$ $\varepsilon_z = -\nu \frac{\sigma_x}{E}$

6 stress strain Equations

$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - \nu \cdot \left(\sigma_y + \sigma_z\right)\right]$$

$$\varepsilon_y = \frac{1}{E}\left[\sigma_y - \nu \cdot \left(\sigma_x + \sigma_z\right)\right]$$

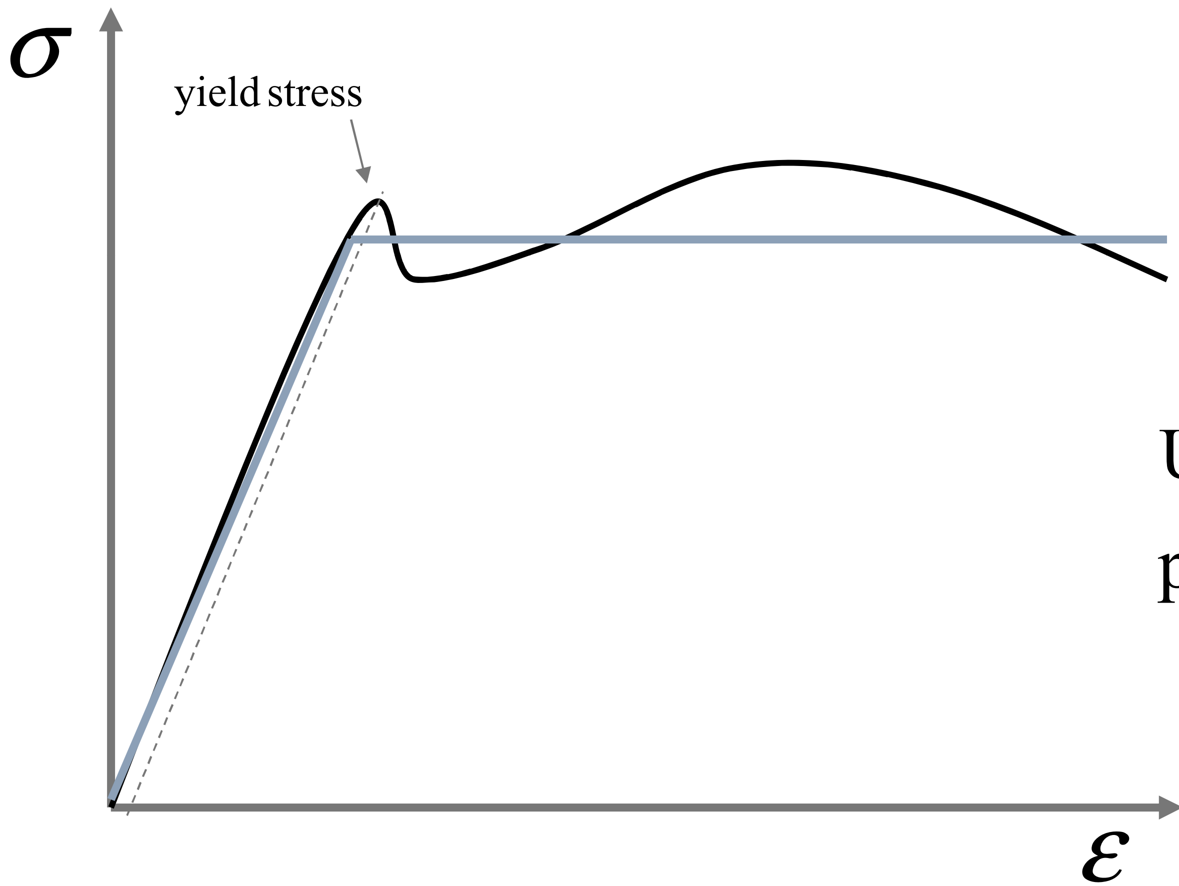
$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \nu \cdot \left(\sigma_x + \sigma_y\right)\right]$$

$$\sigma_{xy} = \frac{\tau_{xy}}{G}$$

$$\sigma_{yz} = \frac{\tau_{yz}}{G}$$

$$\sigma_{zx} = \frac{\tau_{zx}}{G}$$

Typical Material (Metal)



Use linear elastic perfectly plastic model

Thermal Strains

$$\varepsilon_x^\theta = \varepsilon_y^\theta = \varepsilon_z^\theta = \alpha\,\Delta\theta = \alpha\left(\theta - \theta_o\right)$$

$$\alpha = \text{coefficient of thermal expansion}$$

$$\gamma_{xy}^\theta = \gamma_{yz}^\theta = \gamma_{zx}^\theta = 0$$

total strain=elastic strain + thermal strain

$$\varepsilon^t = \varepsilon^{\mathrm{e}} + \varepsilon^\theta$$

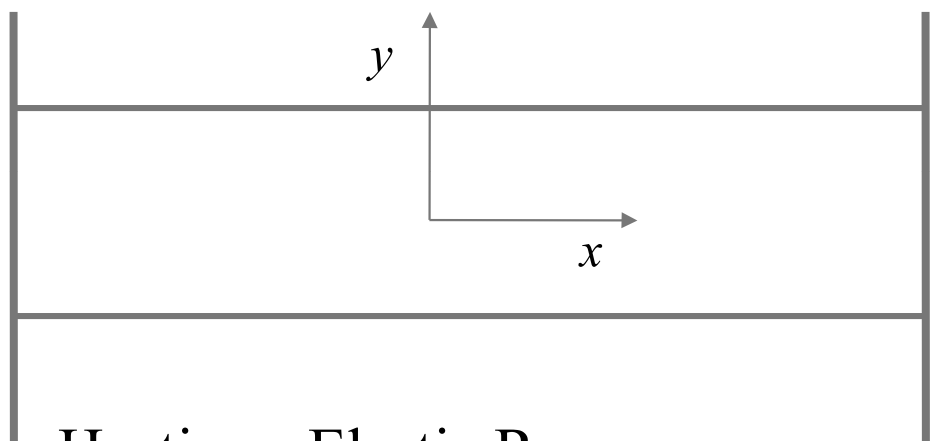
Linear Elastic Perfectly Plastic Material

$$\varepsilon^{t} = \varepsilon^{e} + \varepsilon^{p} + \varepsilon^{\theta}$$

elastic (ε^{e}) plastic (ε^{p}) thermal (ε^{θ})

Example

- Steel Bar between two rigid walls



$$E = 20\times10^{6} \ \text{psi}$$

$$F_y = 50\times10^{3} \ \text{psi}$$

$$\alpha = 3.8\times10^{-6} \frac{1}{{}^{o}F}$$

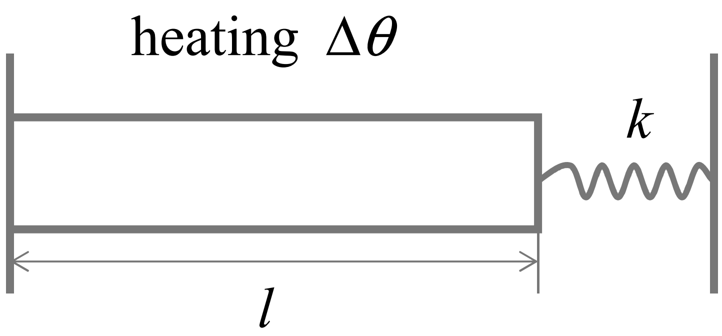
Heating - Elastic Range

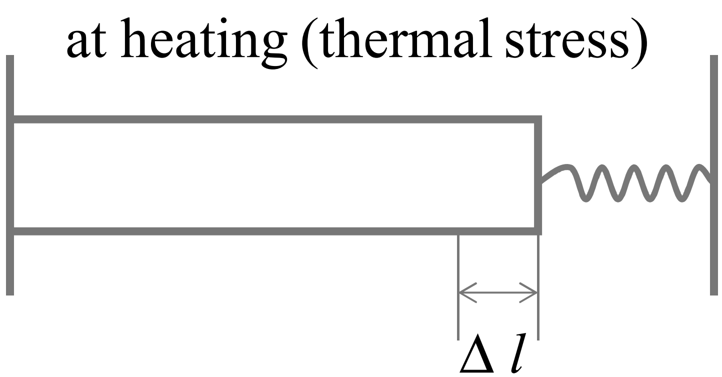
$$\varepsilon_x^t = 0 = \frac{\sigma_x}{E} + \alpha\,\Delta\theta$$

$$\therefore \quad \sigma_x = -\alpha\,E\Delta\theta = -114\,\frac{\text{psi}}{{}^{o}F}\Delta\theta$$

Simple Distortion Example (Transverse Shrinkage)

- Restraint and Temp. Distribution





Heating

$$\varepsilon_x = \frac{\Delta l}{l} = \frac{\sigma_x}{E} + \alpha\,\Delta\theta + \varepsilon^p$$

$$\sigma_x A = -k\Delta l \rightarrow \Delta l = -\frac{\sigma_x}{k} A$$

$$\therefore \quad -\frac{\sigma_x}{kl} A = \left(\frac{\sigma_x}{E} + \alpha\,\Delta\theta + \varepsilon^p \right)$$

$$\therefore \quad \sigma_x = -\frac{E\,k\,l\left(\alpha\,\Delta\theta + \varepsilon^p\right)}{E\;A + k\,l}$$

Small Δθ

No plastic strain $\varepsilon^{p} = 0$

Then,

$$\sigma_x = -\frac{EKl(\alpha \cdot \Delta\theta)}{EA + Kl}$$

At the end of cooling there will be no residual stress and no distortion.

Large Δθ – at end of heating

Assume $\varepsilon^p = 0$

Calculate $\sigma_x = -\dfrac{EKl(\alpha \cdot \Delta\theta)}{EA + Kl}$

If $|\sigma_x| > F_y$ **then,** $\varepsilon^p \neq 0$ **and** $\sigma_x = -F_y$

$$\varepsilon^p = F_y\left(\frac{A}{Kl} + \frac{1}{E}\right) - \alpha \cdot \Delta\theta$$

Large Δθ – at end of Cooling

Assume no additional plastic deformation occurs during cooling.

Calculate $$\sigma_x = \frac{EKl\left(\varepsilon^p\right)}{EA+Kl}$$

If $\sigma_x < F_y$ then, no plastic deformation occurred

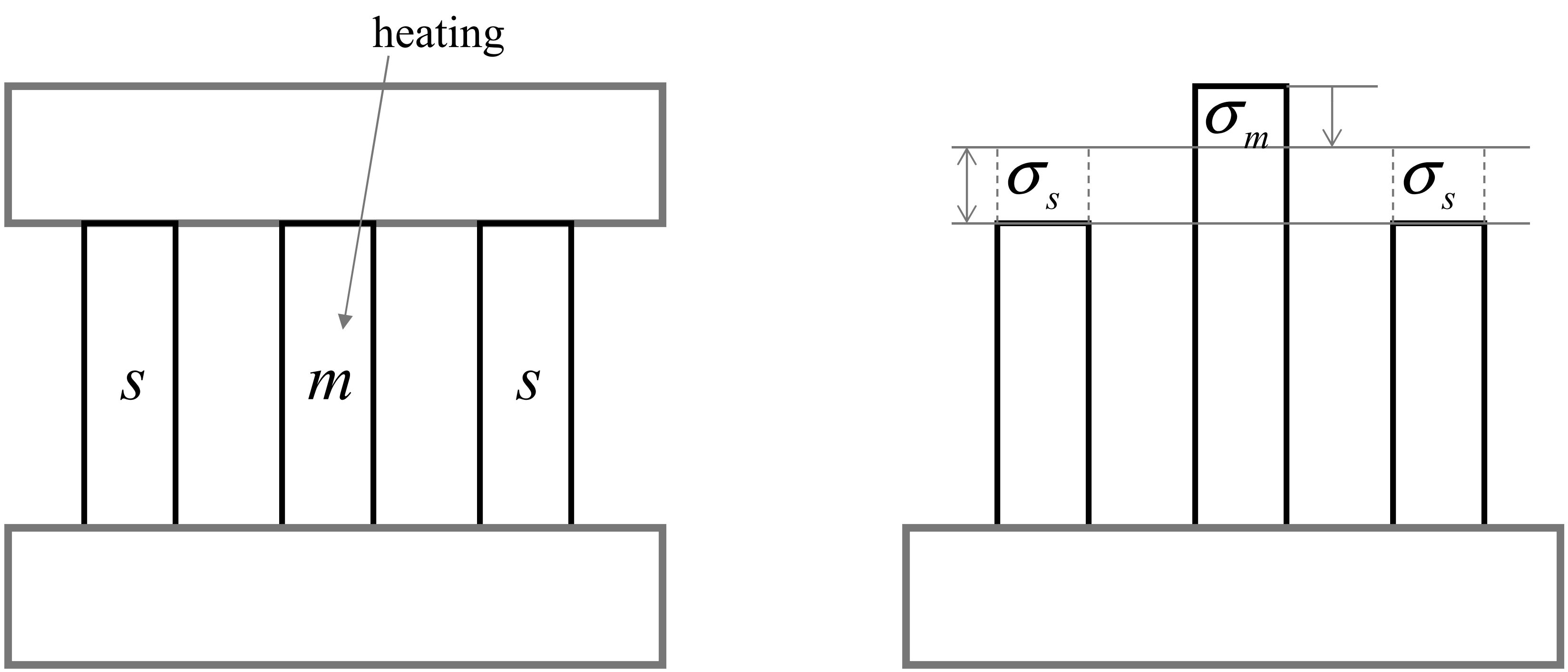
during cooling, and $$\sigma_{xres} = \frac{EKl\left(\varepsilon^p\right)}{EA+Kl}$$

If $\sigma_x > F_y$ then, plastic deformation occurred

during cooling, and $$\sigma_x = F_y \qquad \varepsilon^p = -F_y\left(\frac{A}{Kl}+\frac{1}{E}\right)$$

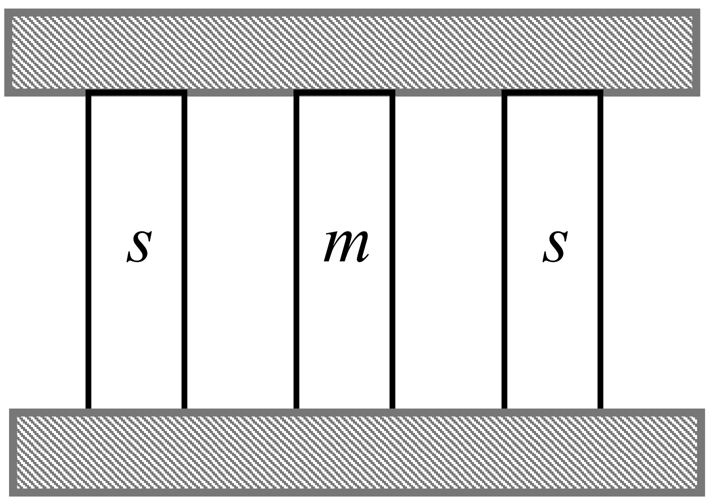
Three Bar Analogy

- Suppose we have 3-bar which have the same cross section area A and same material properties.



Three Bar Analogy

- Jig or fixture used (restraint) during heating
  - Small heating



$$\therefore \quad \varepsilon_{tm} = \frac{\sigma_m}{E} + \alpha\,\Delta\theta + \varepsilon_m^p, \quad \varepsilon_m^p = 0$$

$$\therefore \quad \sigma_m = -\alpha\,\Delta\theta \cdot E \qquad \text{comp. spring case}$$

$$\varepsilon^p = 0$$

$$\varepsilon_{tx} = 0$$

Significance of Residual Stress and Distortion

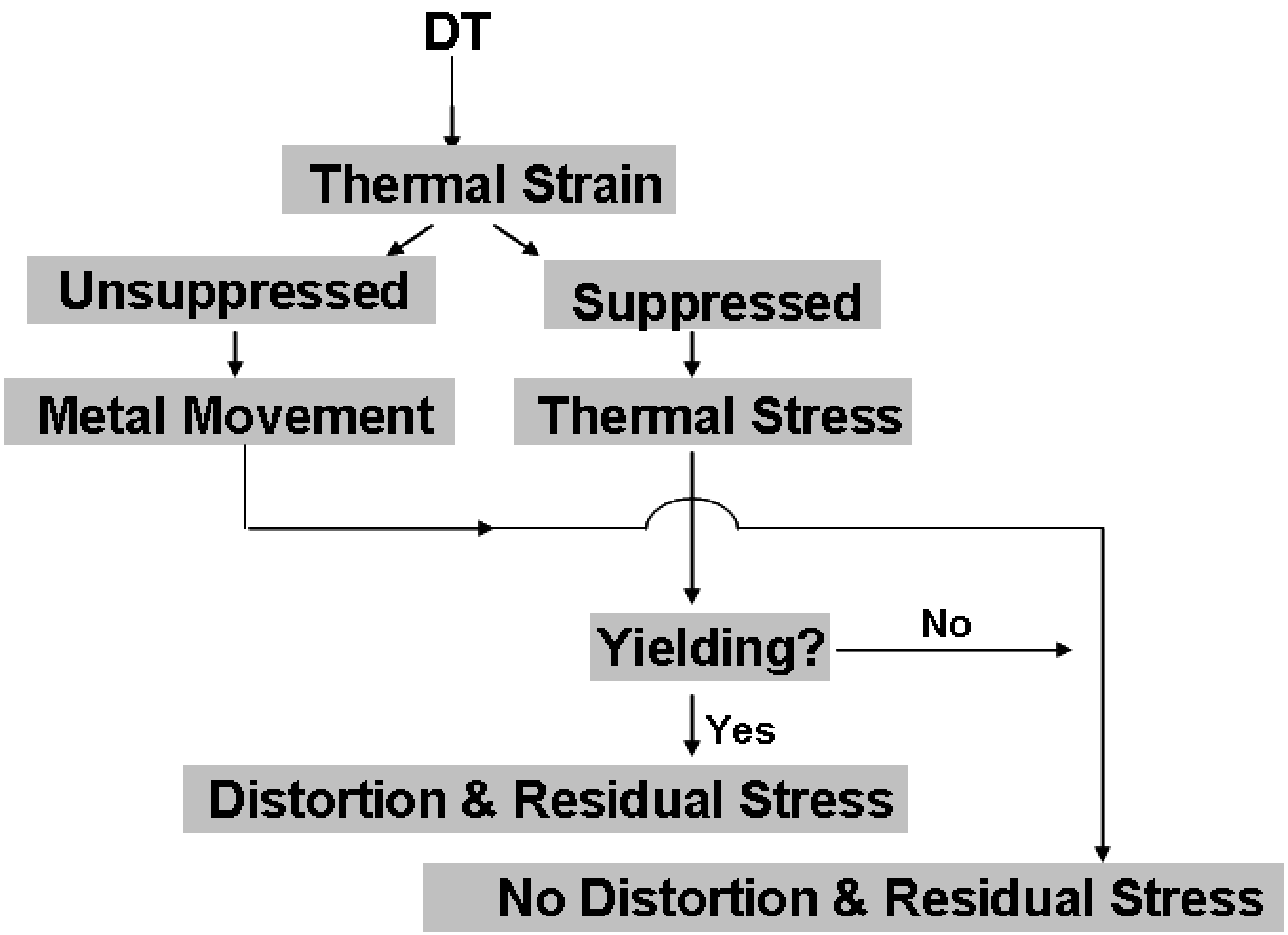
- Residual Stress
  - Degraded Structural Performance
  - Reduced Service Life
  - Dimensional Instability
- Distortion
  - Dimensional Tolerance and Fit-up Problems
  - Reduced Strength
  - Reduced Structural Stability
  - Inadequate Appearance

Welding Processes and Their Consequences

- During Welding
  - Localized Heat Source (heating, melting solidification, and cooling)
  - Non-uniform Temperature Distribution (thermal/mechanical mismatch)
  - Fast Cooling Rate (phases with volume expansion)
  - Weld Shrinkage (shrinkage strains created in weld & surrounding metal)
  - Restraints (internal rigidity and/or external constraints preventing shrinkage)
  - Initial Stress Condition (influence thermal strain and residual stress)
  - Properties of Parent Material (temperature dependent yield stress and Modulus of elasticity)

After Welding
- **Residual Stresses**
- **Distortion**

Residual Stresses & Distortion Flowchart



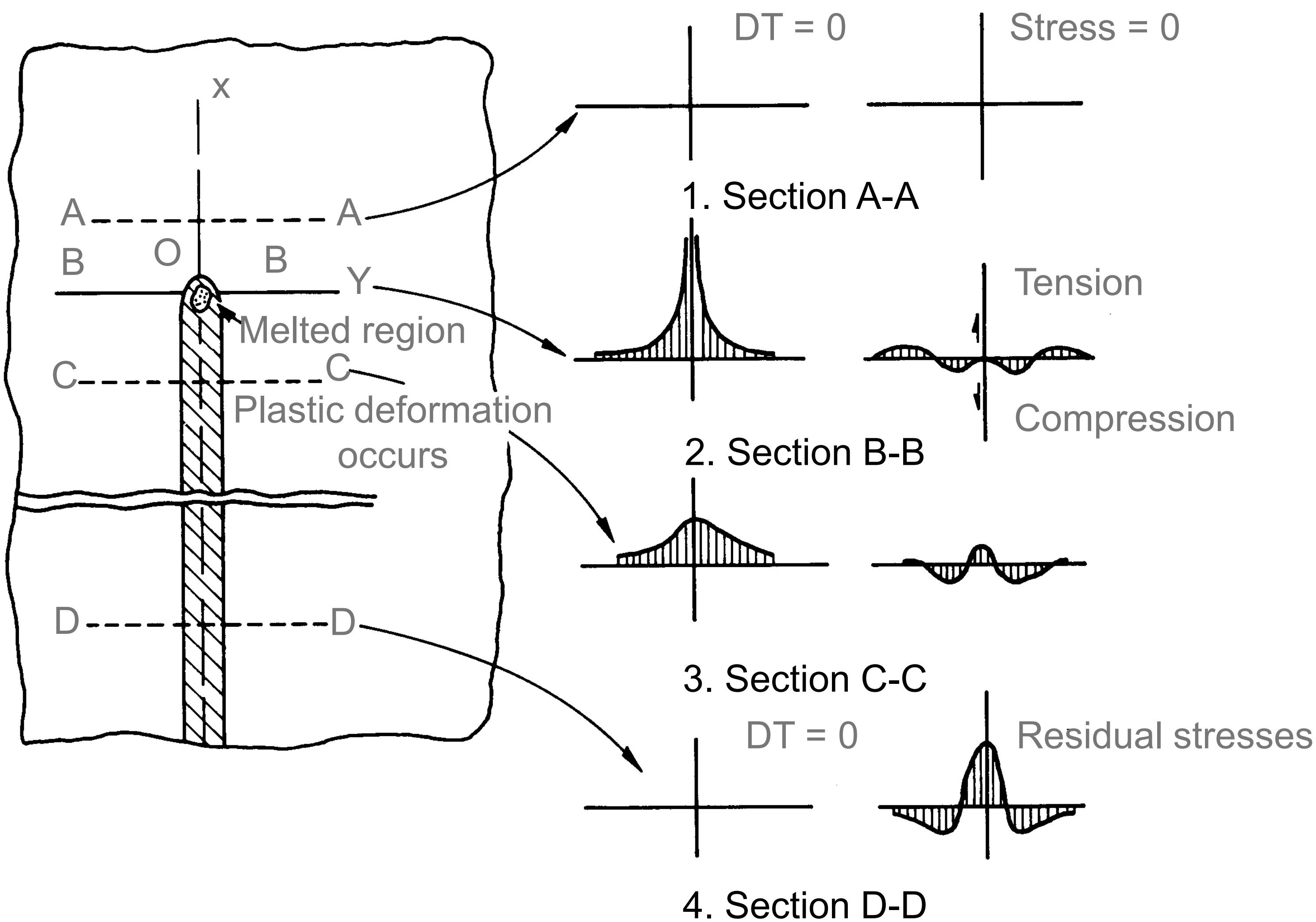
Factors Influencing Residual Stresses & Distortion

- Physical Material Properties
  - Coefficient of thermal expansion, [α (1/°K)]
    - As α increases distortion increases
  - Thermal conductivity, λ (W/(m·°K))
    - As λ increases distortion decreases
- Mechanical Material Properties
  - Yield stress, F_y (ksi), modulus of elasticity, E(ksi)
- Welding Process Variables
  - Heat input, travel speed, welding sequence
- Jigs and Fixtures or other Clamping Devices
- Geometrical Properties
  - Moment of inertia, weld cross sectional area, weight of weld metal, plate thickness, joint geometries, weld length

Comparison of Material Properties

Properties / Materials	Mechanical Properties				Thermal Properties				
	F_{ult} [MPa]	F_y [MPa]	e [%]	E [GPa]	CTE 20 °C [mm/m°C]	rC_p [J/m³/°C]x10⁶	l [W/m-K]	T_m [°C]	T_{liq} [°C]
NICKEL BASE INCONEL 718	1375	1100	25	207	13	3.56	11.4	1298	1336
TITANIUM TI-6AL-4V	1170	1100	10	114	8.6	2.33	6.7	1660	1660
ALUMINUM 2014	185	95	18	72.4	23	2.46	192	507	638
STAINLESS STEEL 304	505	215	70	197	17.3	4.00	16.2	1427	1455

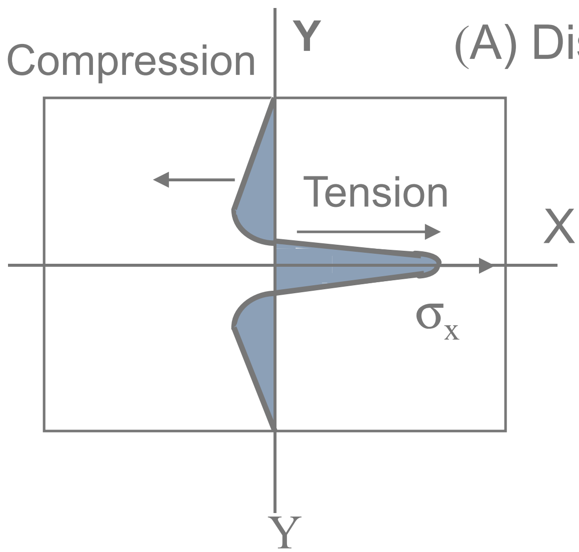
Non-Linear Distribution of Temperature and Resulting Residual Stress

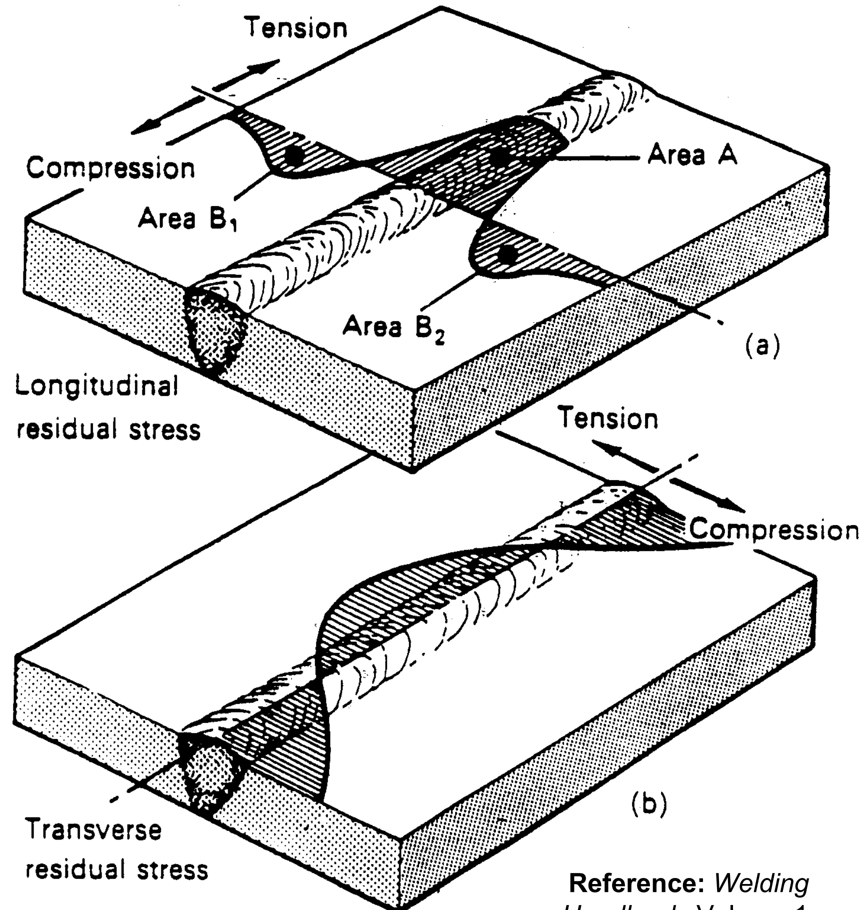


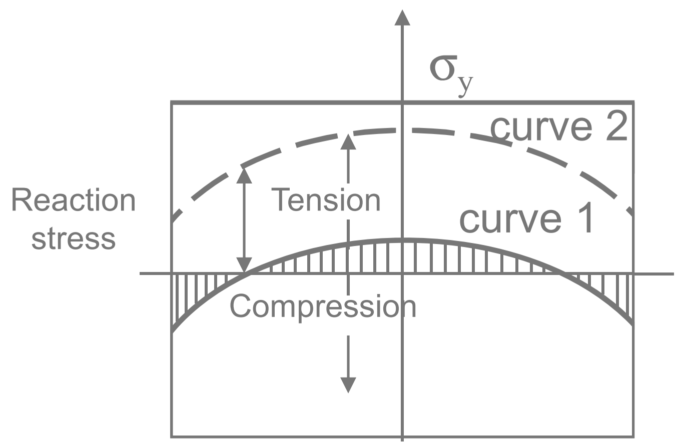
Reference: *Welding Handbook,* Volume 1, AWS, 1991

Residual Stresses in Butt Joint

(A) Distribution of σ_x Along YY



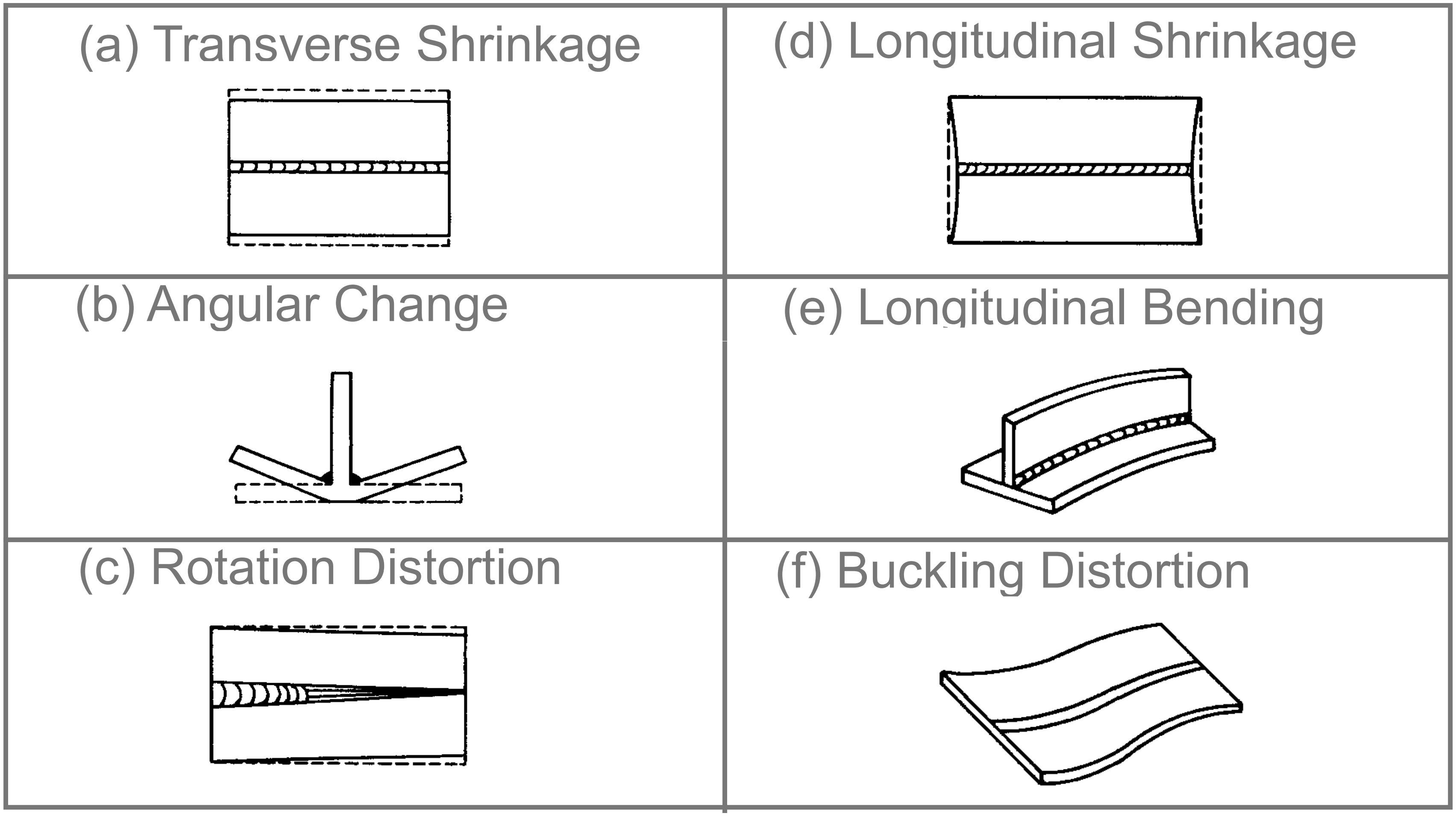




Reference: *Welding Handbook,* Volume 1, AWS, 1991

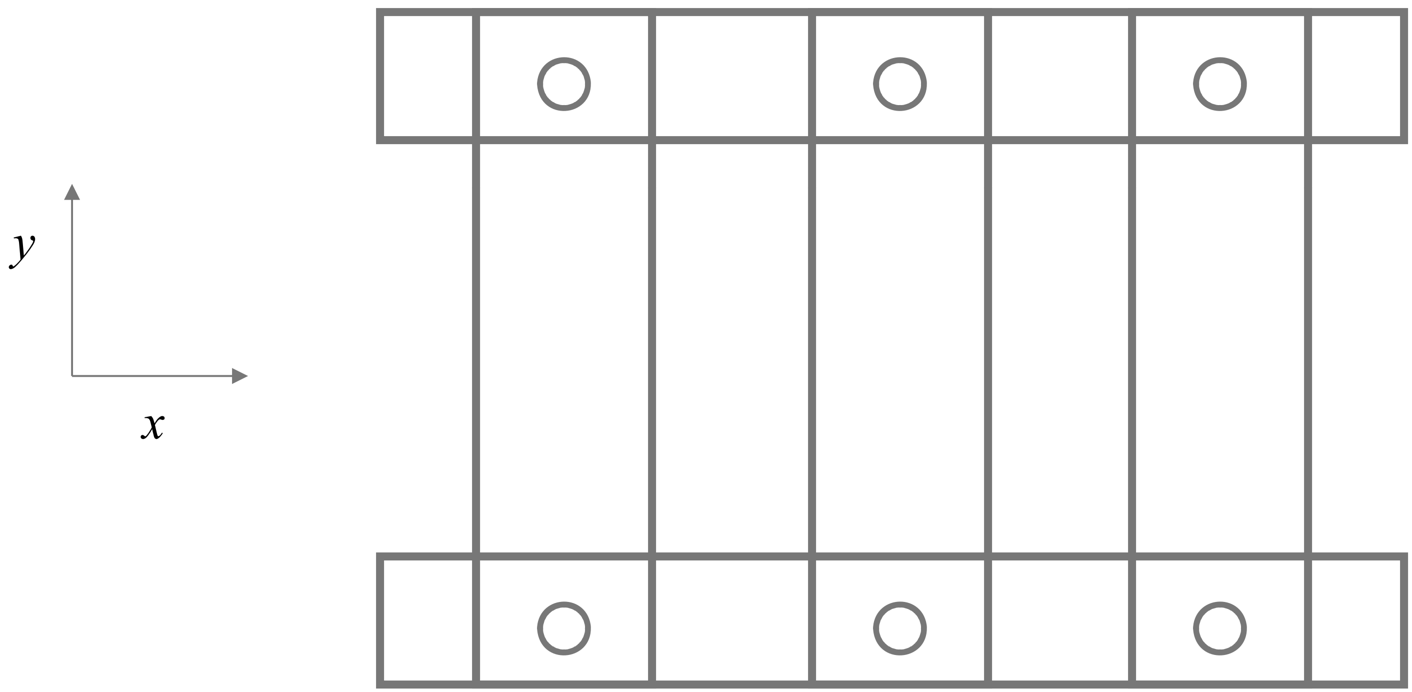
(B) Distribution of σ_y Along XX

Fundamental Types of Weld Distortion



Reference: *Welding Handbook,* Volume 1, AWS, 1991

Compatibility



Compatibility

2-D Elastic Compatibility

$$R = \frac{\partial^2 \varepsilon_x}{\partial y^2} + \frac{\partial^2 \varepsilon_y}{\partial x^2} - \frac{\partial^2 \gamma_{xy}}{\partial x \, \partial y} = 0$$

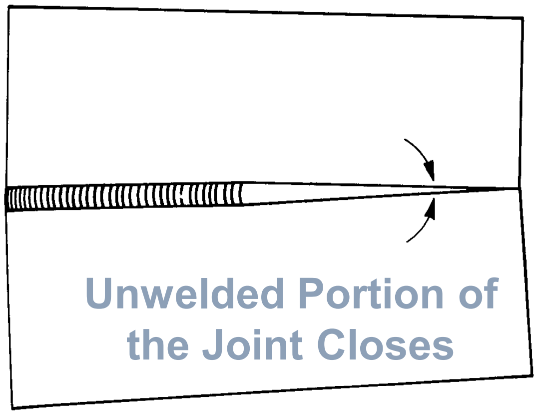
2-D Inelastic Compatibility

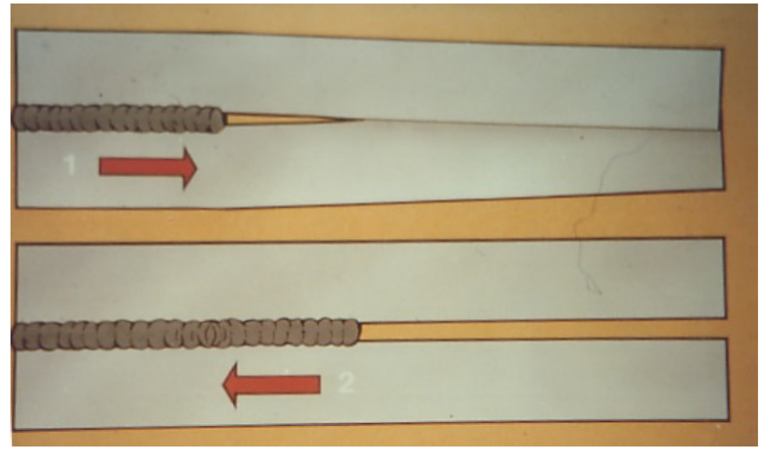
$$R' + R'' = \underbrace{\left[\frac{\partial^2 \varepsilon'_x}{\partial y^2} + \frac{\partial^2 \varepsilon'_y}{\partial x^2} - \frac{\partial^2 \gamma'_{xy}}{\partial x \, \partial y} \right]}_{\text{Elastic}} + \underbrace{\left[\frac{\partial^2 \varepsilon''_x}{\partial y^2} + \frac{\partial^2 \varepsilon''_y}{\partial x^2} - \frac{\partial^2 \gamma''_{xy}}{\partial x \, \partial y} \right]}_{\text{Inelastic (thermal \& plastic)}} = 0$$

Elastic

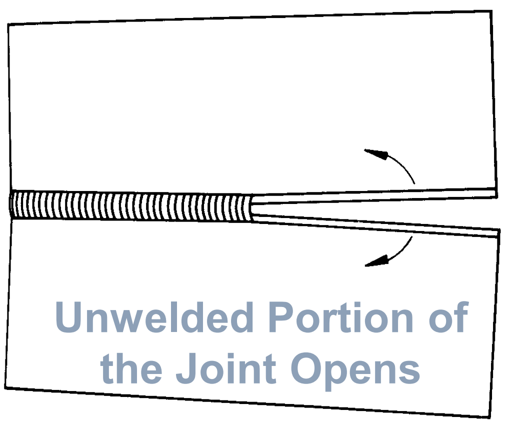
Inelastic
(thermal & plastic)

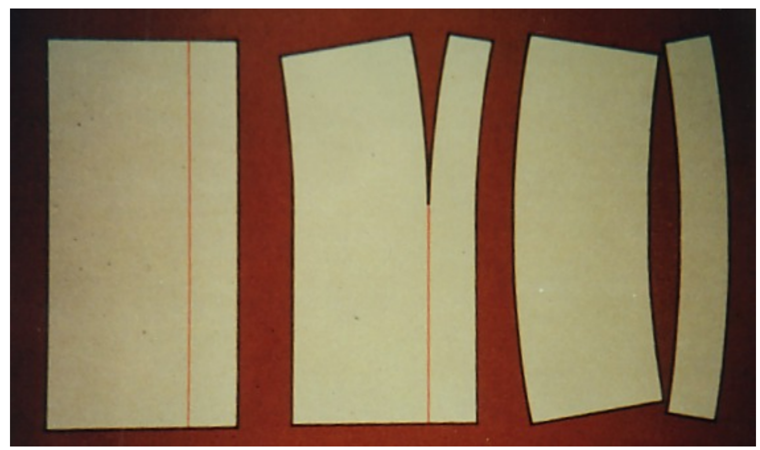
Rotational Distortion in Butt Joints





Back Weld to Maintain Joint Opening

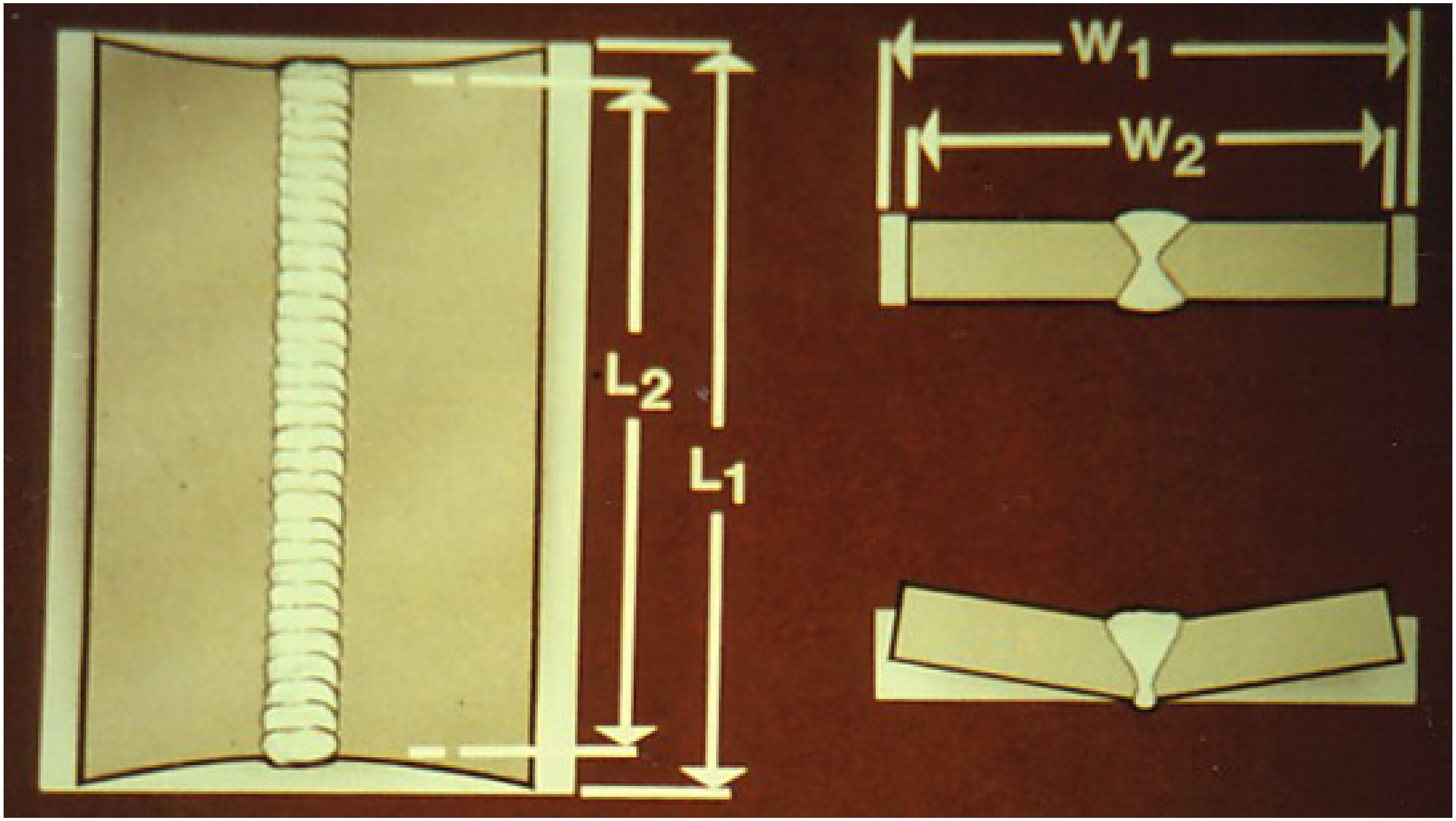




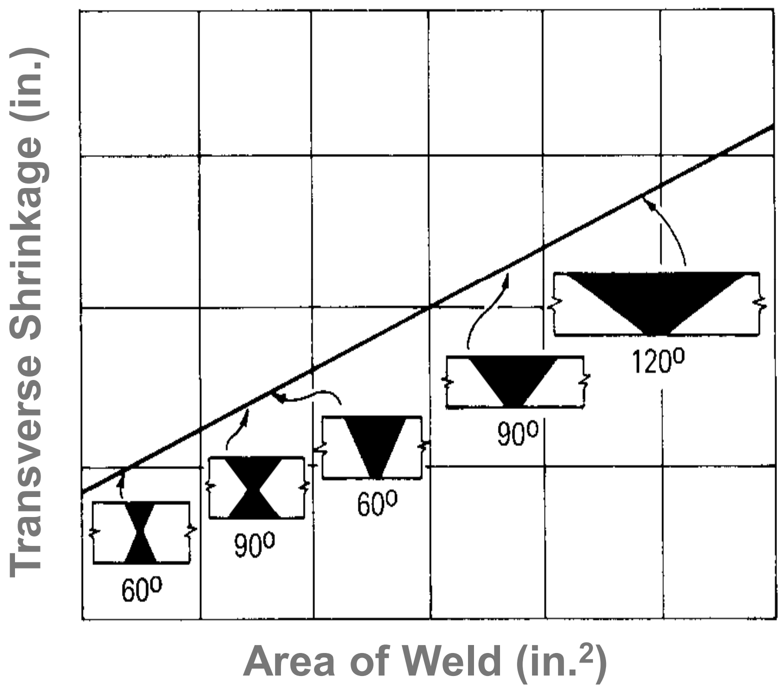
In-Plane Distortion Due to Cutting

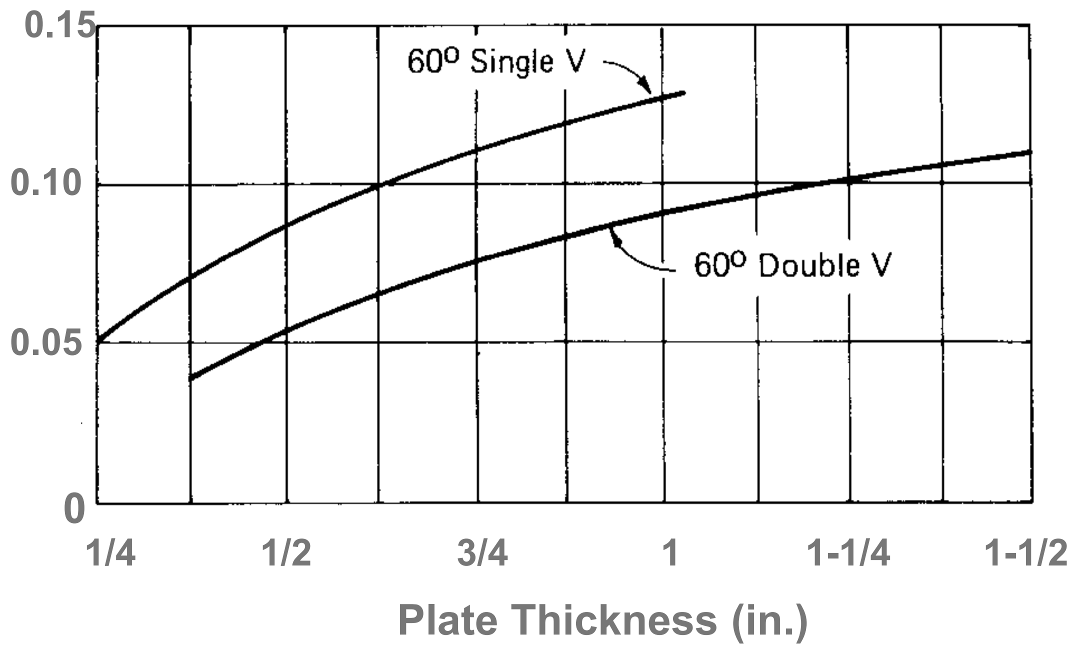
Reference: Masubuchi, K. *Analytical Investigation of Residual Stresses and Distortions Due to Welding. Welding Journal 39 (12): 525s-537s (1960)*

Longitudinal and Transverse Weld Shrinkage in Butt Joints



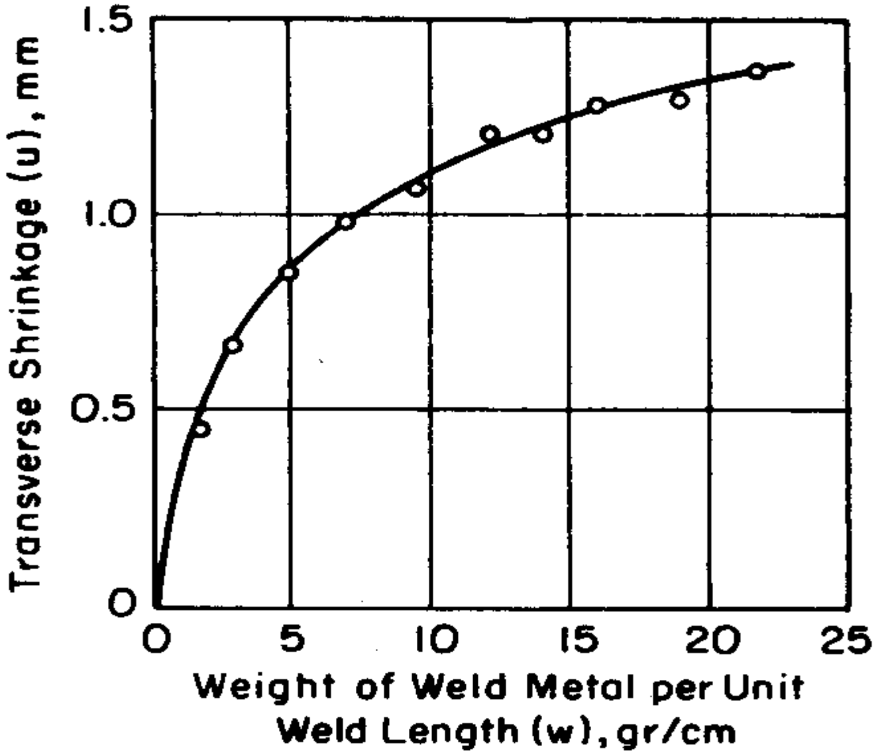
Effect of Groove Detail and Joint Thickness on Transverse Shrinkage



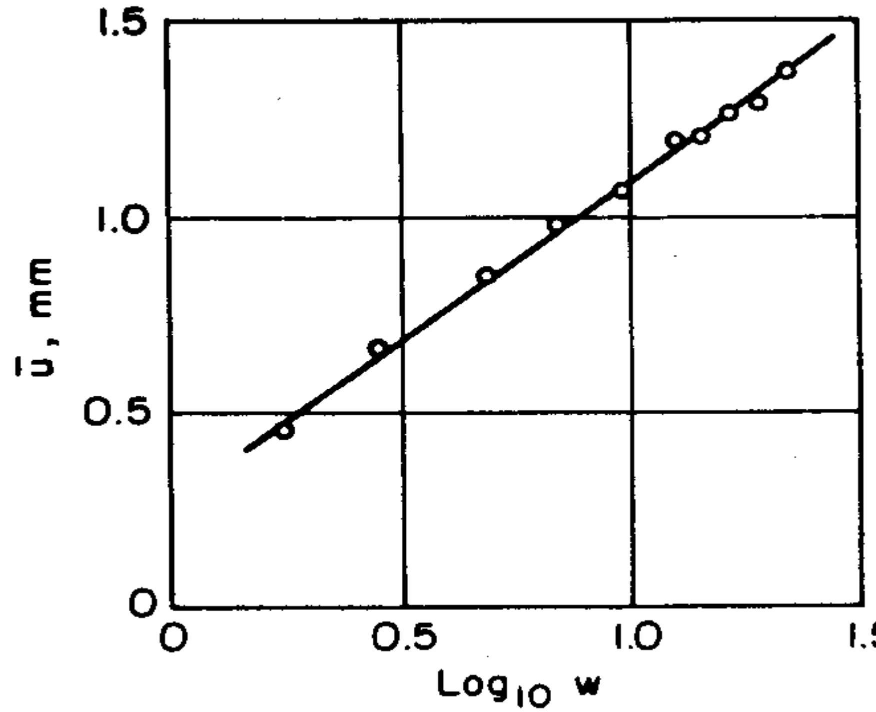


Reference: *Design of Weldments*, Omer W. Blodgett, 1976

Effect of Weight of Weld Metal on Transverse Shrinkage



a. Increase of Transverse Shrinkage in Multipass Welding

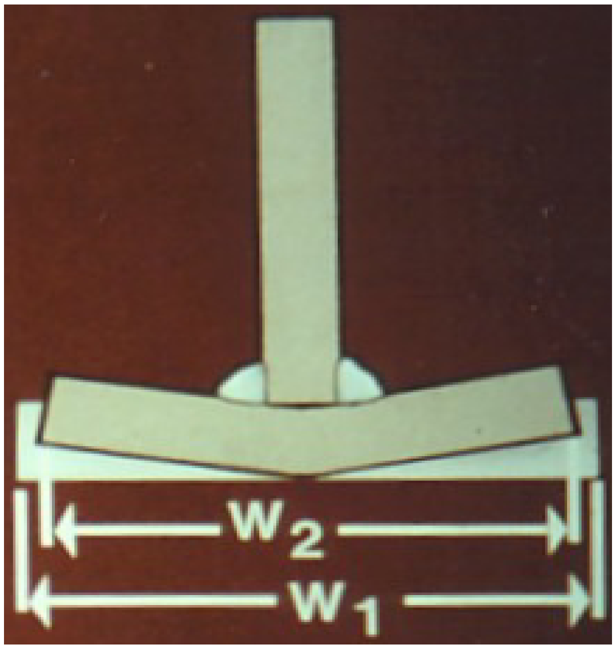


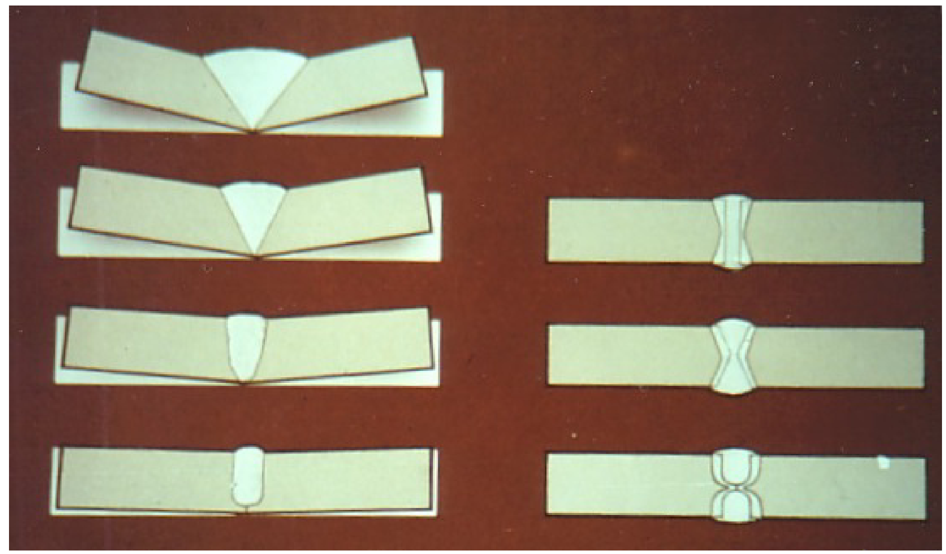
b. Relationship Between log w and u

Increases of Transverse Shrinkage During Multipass Welding of A Butt Joint

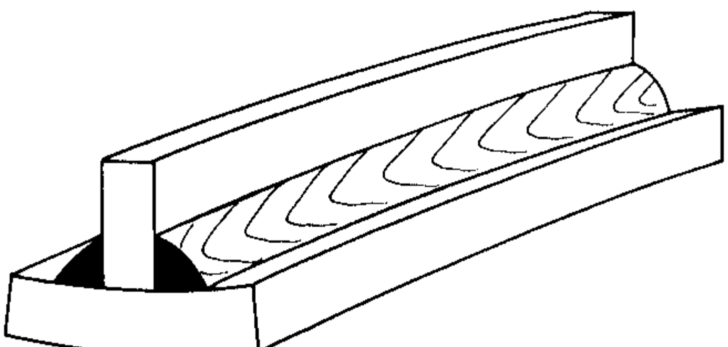
Reference: K. Masubuchi, *Analysis of Welded Structure,* Pergamon Press

Transverse Shrinkage Causing Angular Distortion



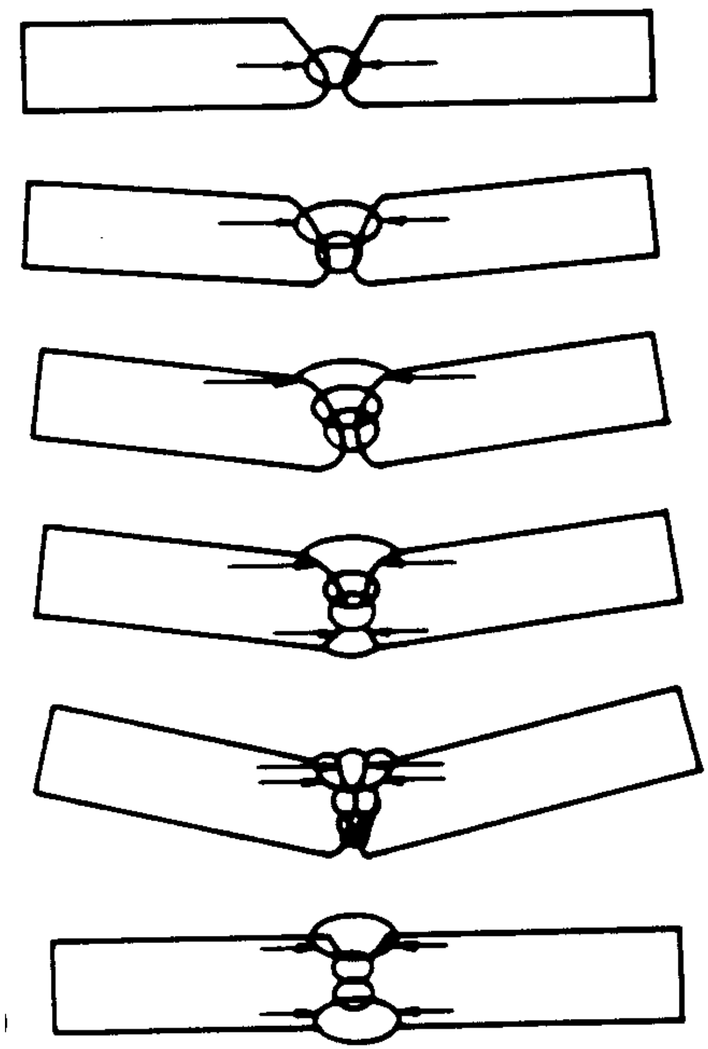


Non-uniform Transverse Weld Shrinkage in Butt Joints



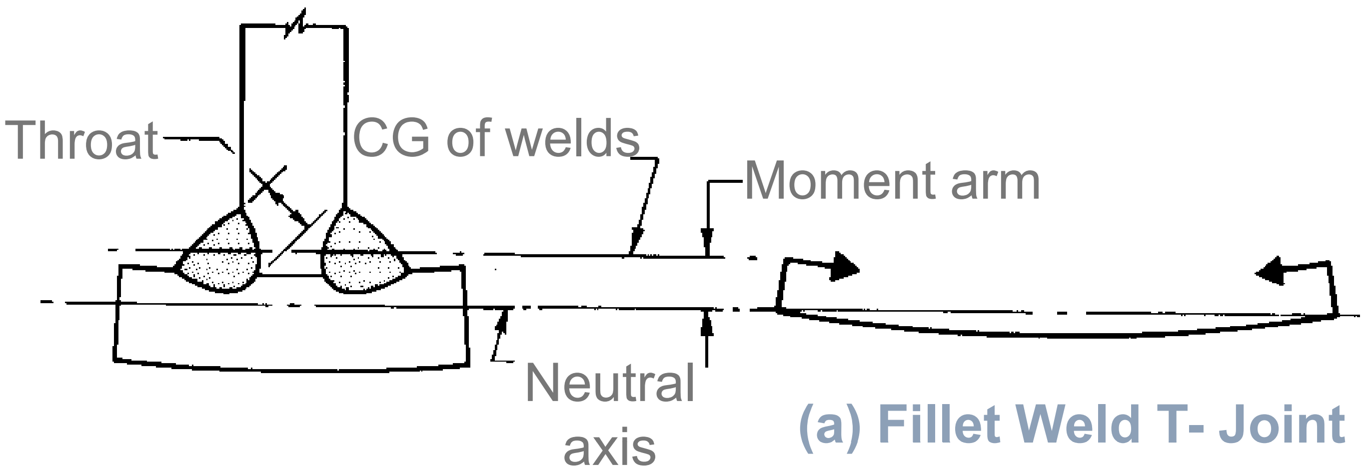
Transverse Weld Shrinkage in Fillet Welded Tee-Joints

Moment of Inertia Effect on Angular Distortion in Butt Joint

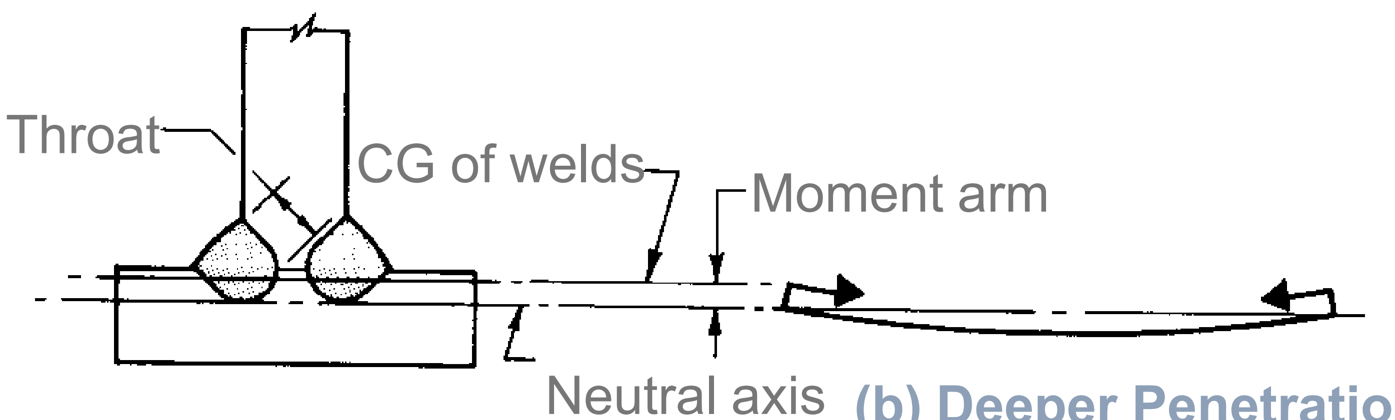


Balancing the Multi-pass Weld Decreases Angular Distortion of Butt Joints

Moment of Inertia Effect on Angular Distortion in Tee-Joint



(a) Fillet Weld T- Joint

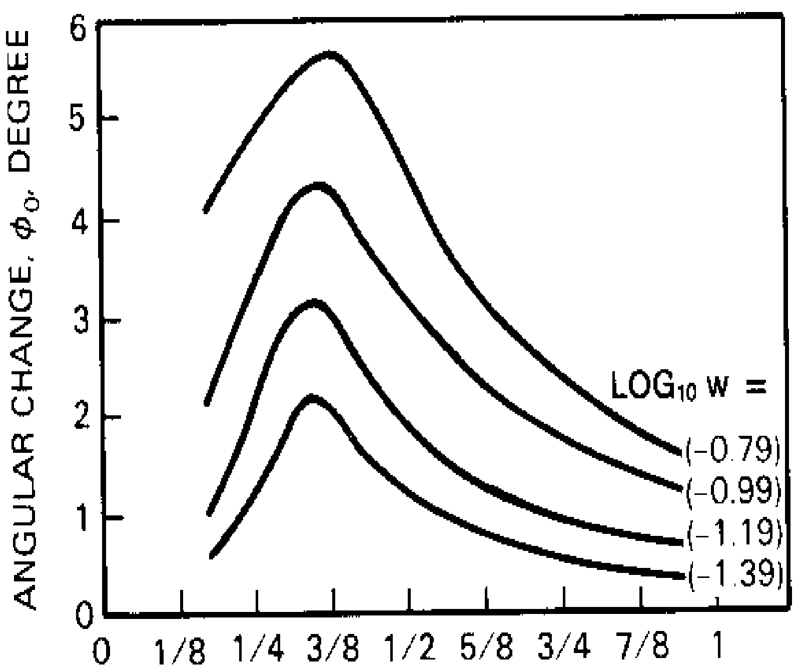


(b) Deeper Penetration Weld

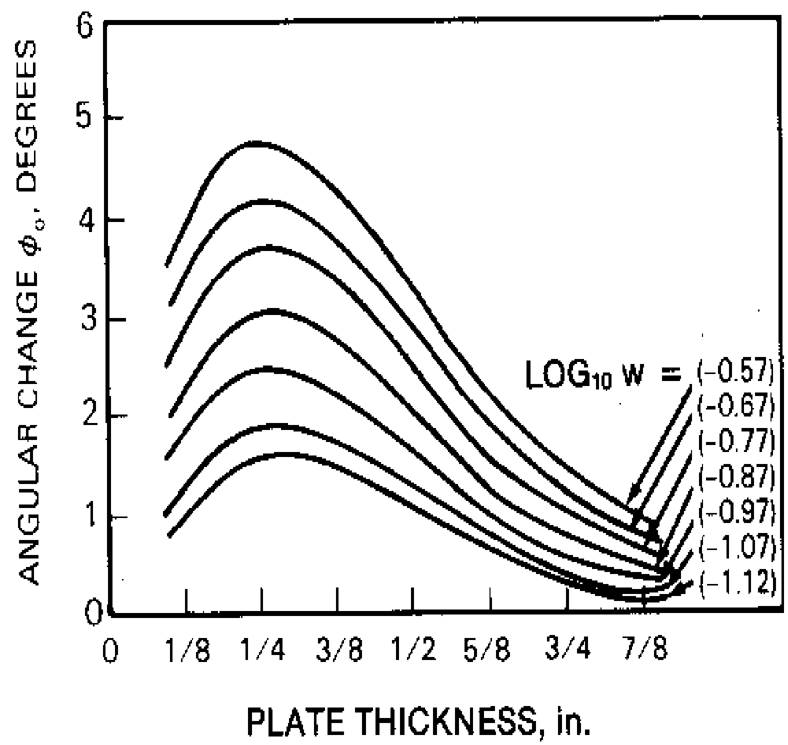
Reference: *Design of Weldments*, Omer W. Blodgett, 1976

Angular Change in Fillet Welds – Unrestrained
Angular Change of Unrestrained Fillet Weld

(A) Steel



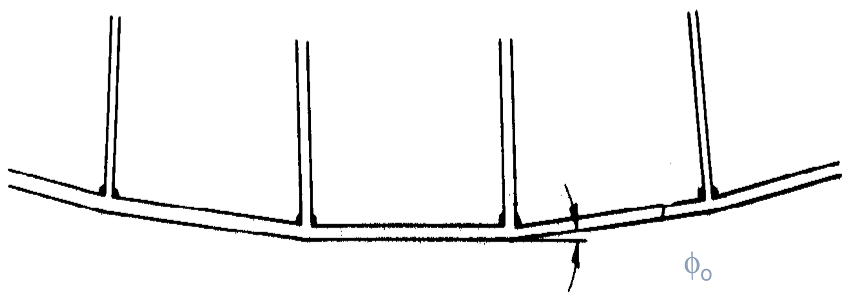
(B) Aluminum



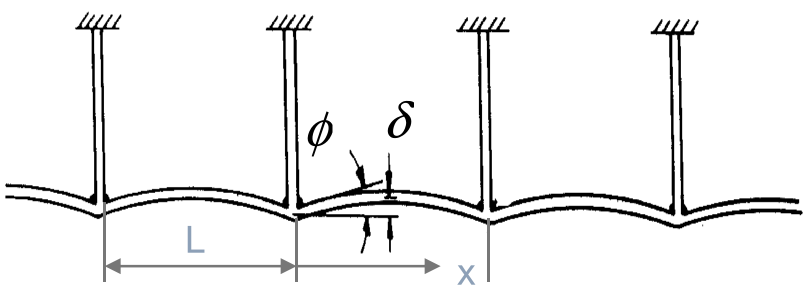
Determination of the Angular Change of Unrestrained Steel and Aluminum Fillet Welds by Plate Thickness and Fillet Weight per Unit Length of Weld

Reference: *Welding Handbook,* Volume 1, AWS, 1991

Angular Distortion in Fillet Welded Framing Structures



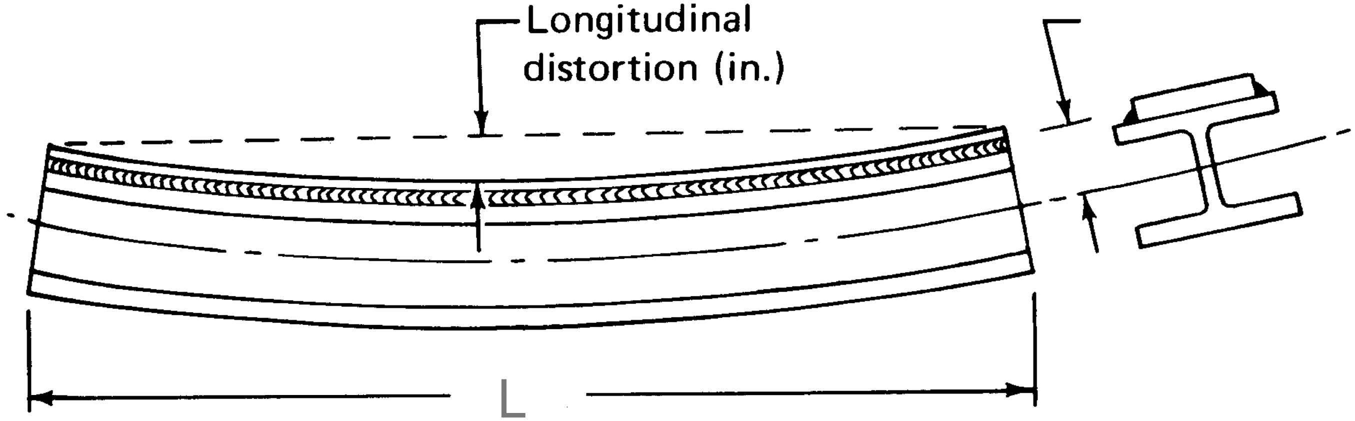
(A) Free Joint (Unrestrained)

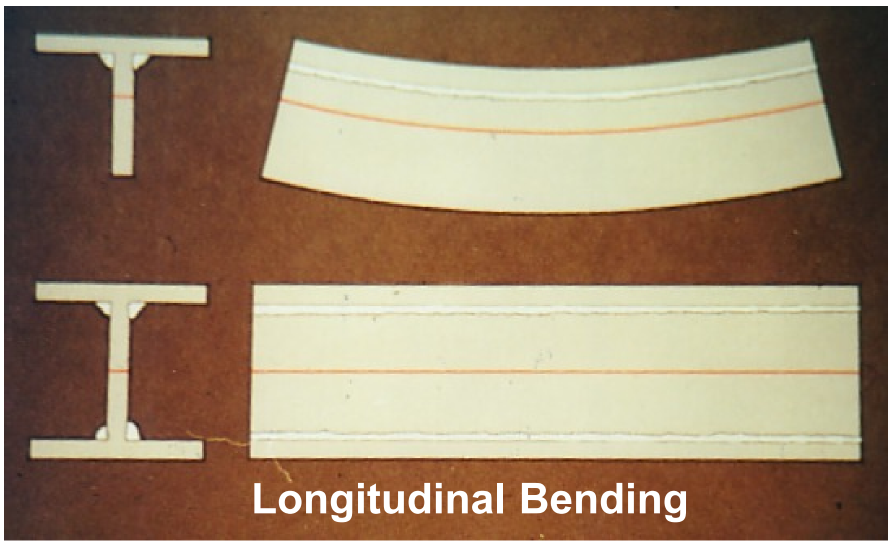


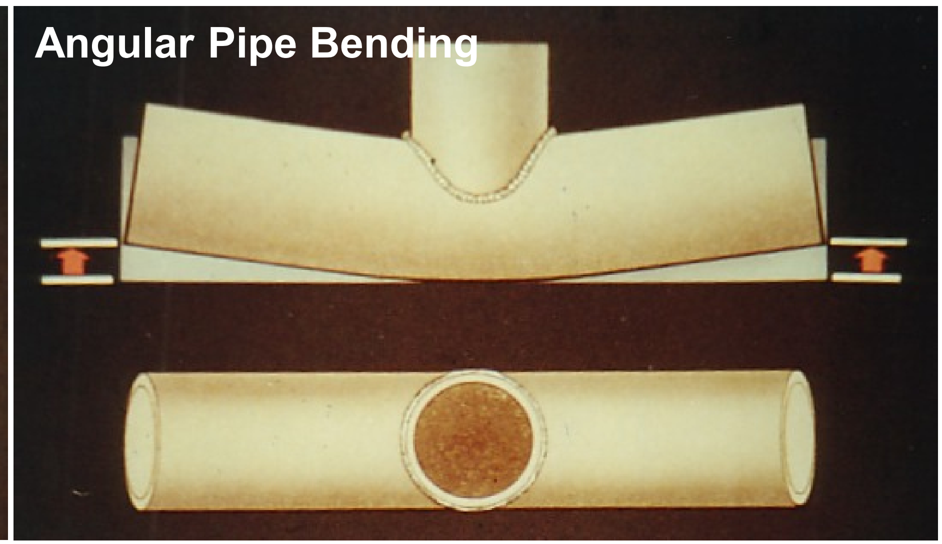
(B) Restrained Joint

Reference: *Welding Handbook,* Volume 1, AWS, 1991

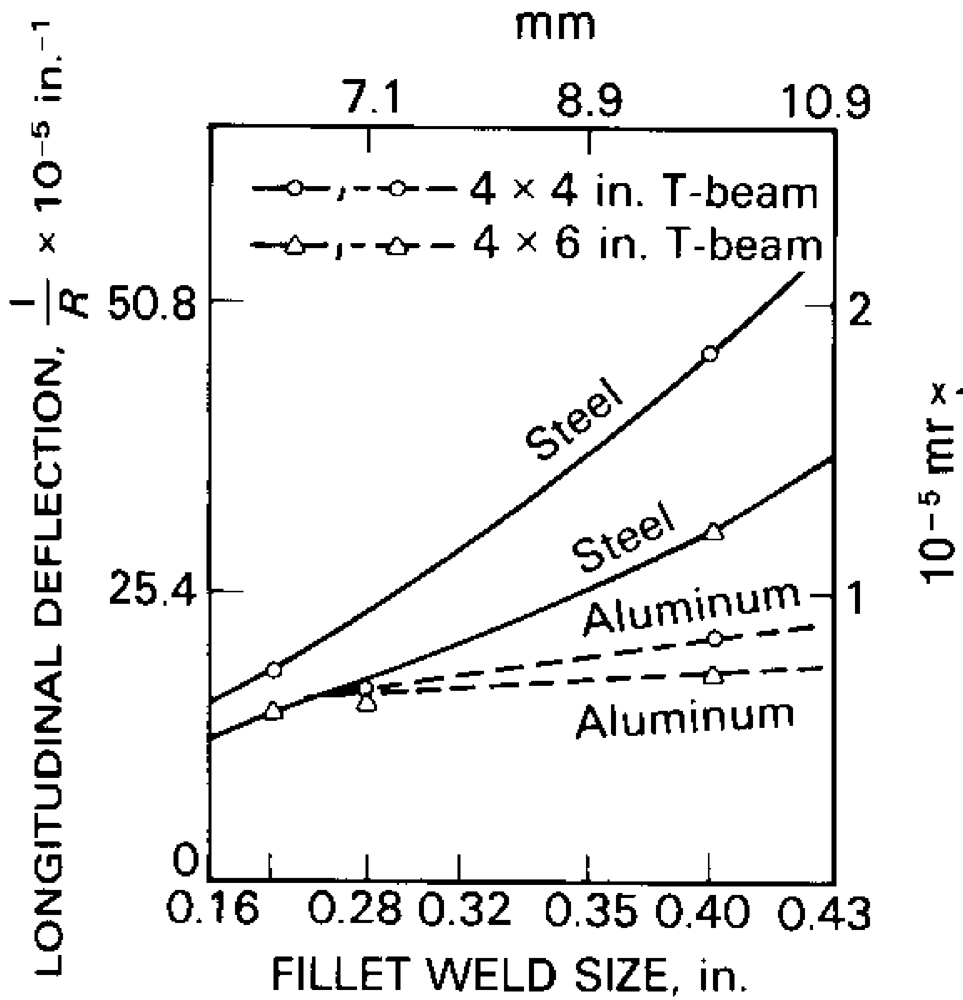
Angular Distortion

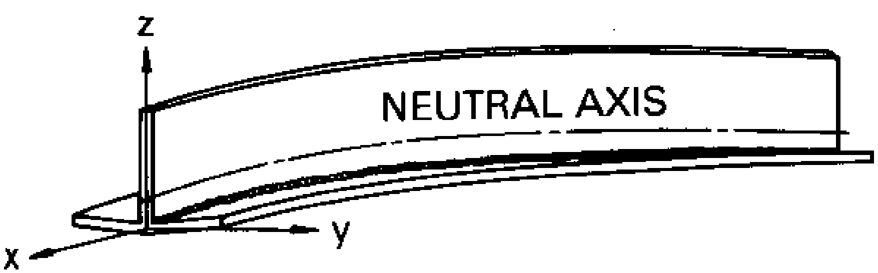






Effect of Fillet Weld Size on Longitudinal Deflection





Effect of Fillet Weld Size on Longitudinal Deflection in T-Section Beams

Reference: *Welding Handbook* Volume 1, AWS, 1991

Distortion Comparison Between Steel and Aluminum Weldments

Transverse Shrinkage of Butt Joint

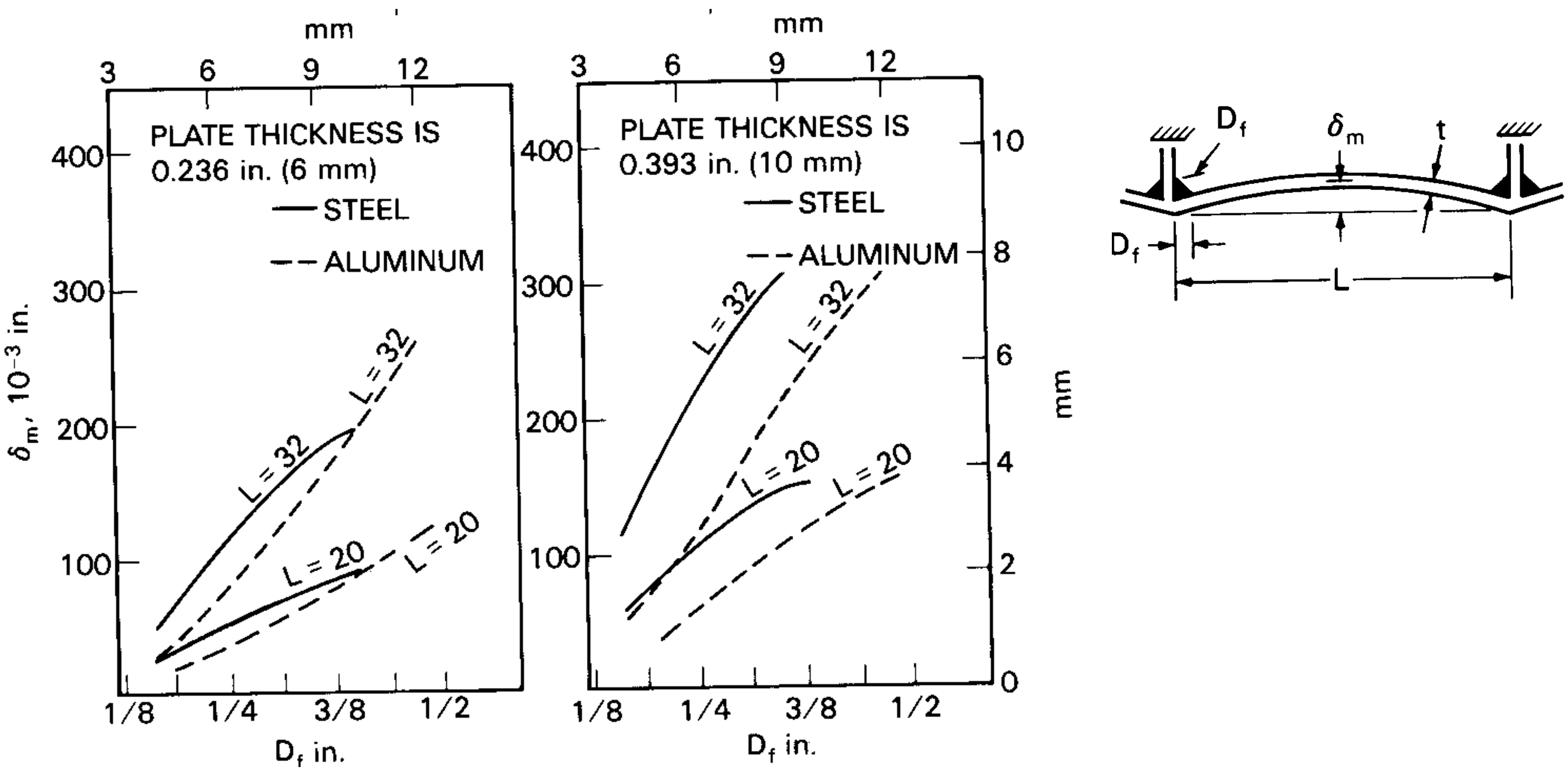
Aluminum > Steel

Longitudinal Bending Distortion

Aluminum < Steel

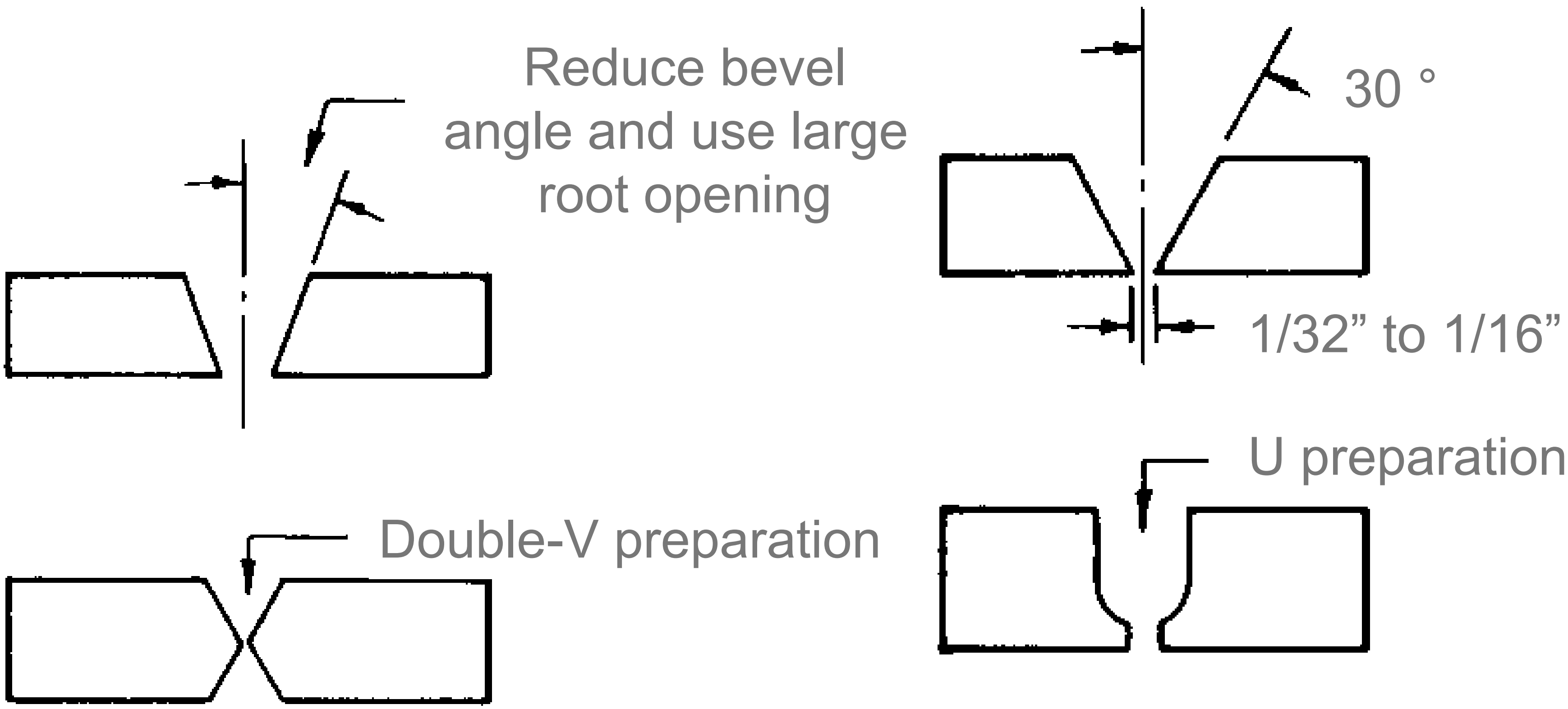
Distortion Comparison Between Steel and Aluminum Weldments

Angular Change of a Fillet Weld   Al < St



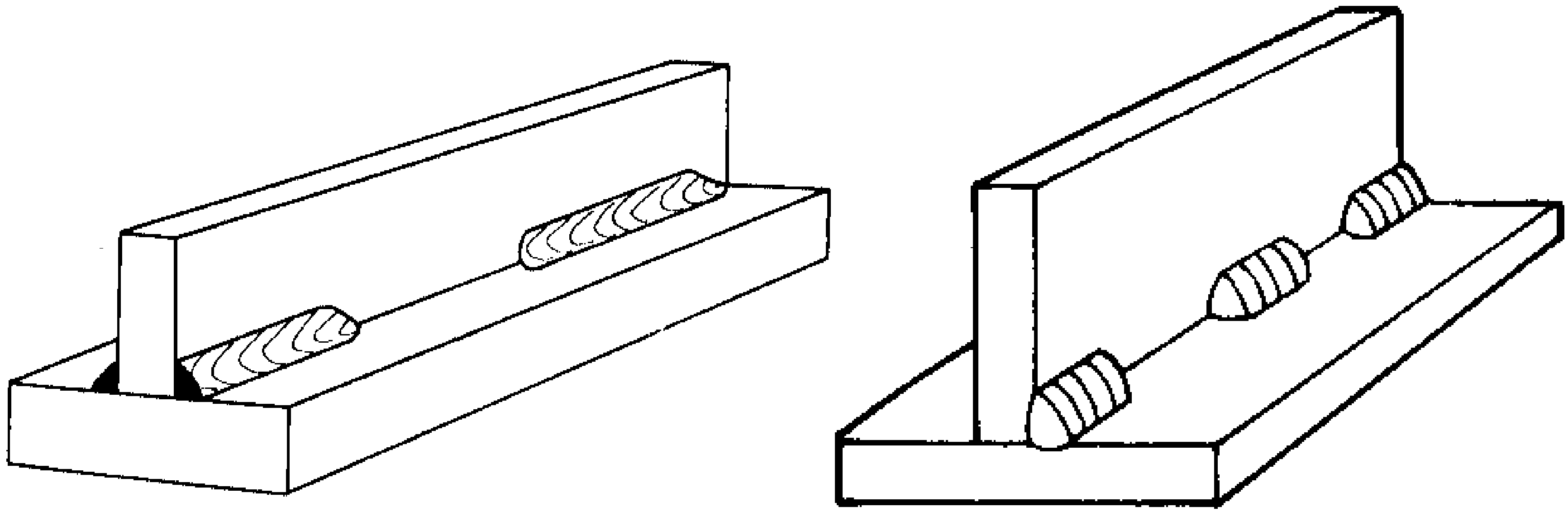
Reference: *Welding Handbook,*Volume 1, AWS, 1991

Reduce the Amount of Welding Decrease Weld Deposit



Example: Edge Preparation and Fitup

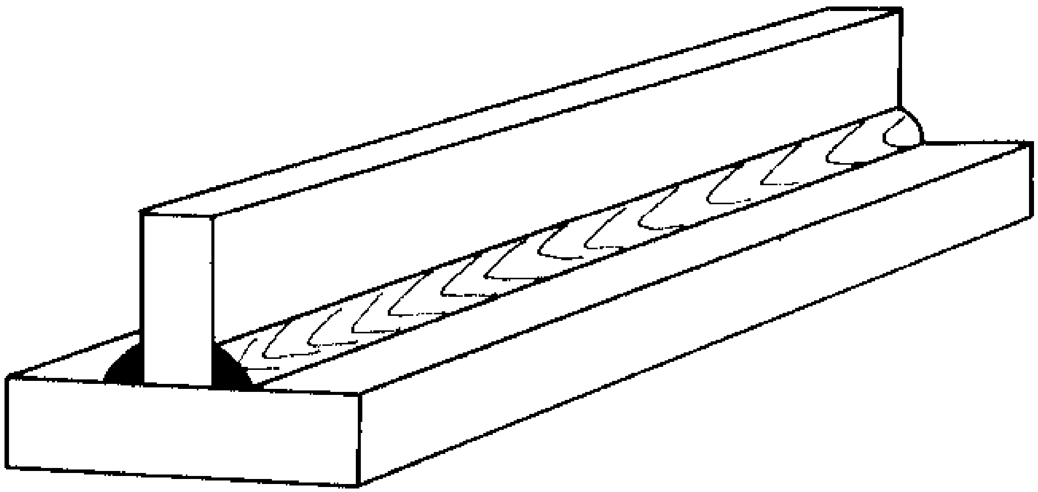
Reduce the Amount of Welding Using Intermittent Welding Technique



Decreasing Length of Weld by Using Intermittent Welding Technique

Reference: *Design of Weldments*, Omer W. Blodgett, 1976

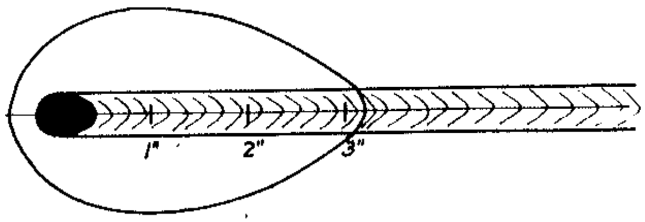
Reduce the Amount of Welding Decrease Leg Size



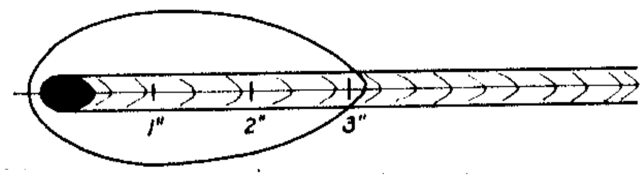
Decrease Leg Size of Weld Decrease Shrinkage Force and the Tendency to Distortion

Reference: *Design of Weldments*, Omer W. Blodgett, 1976

Minimize Welding Time

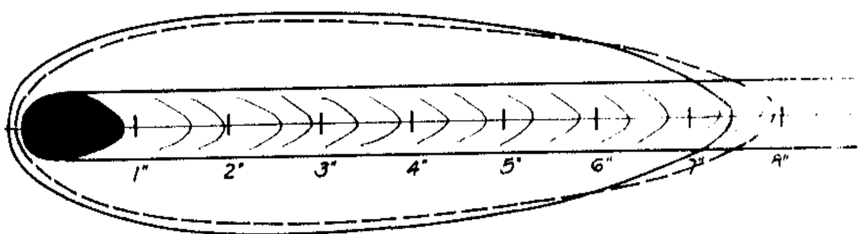


(a) 170 amp 25 volt 3 in/min Thick Plate

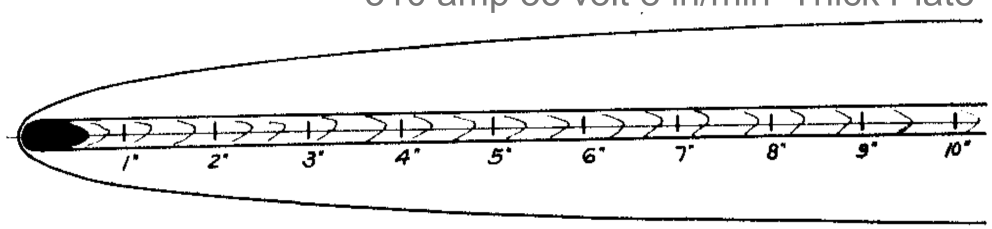


(b) 170 amp 25 volt 6 in/min Thick Plate

Variance of Welding Technique. In Each Case, Surface Isotherm of 300°F is Shown Surrounding Welding Source



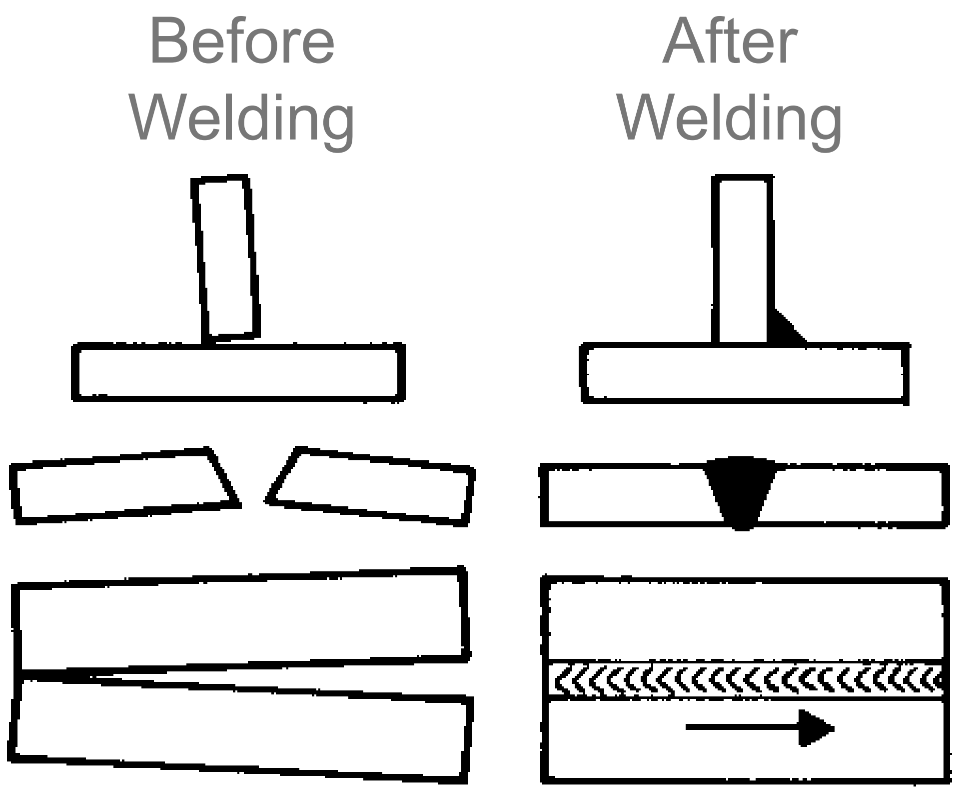
(c) 340 amp 30 volt 6 in/min Thick Plate Solid Curve
310 amp 35 volt 8 in/min Thick Plate Dashed Curve (Same size weld)



(d) 170 amp 25 volt 22 in/min Sheet (t=0.1345 in)

Reference: *Design of Weldments*, Omer W. Blodgett, 1976

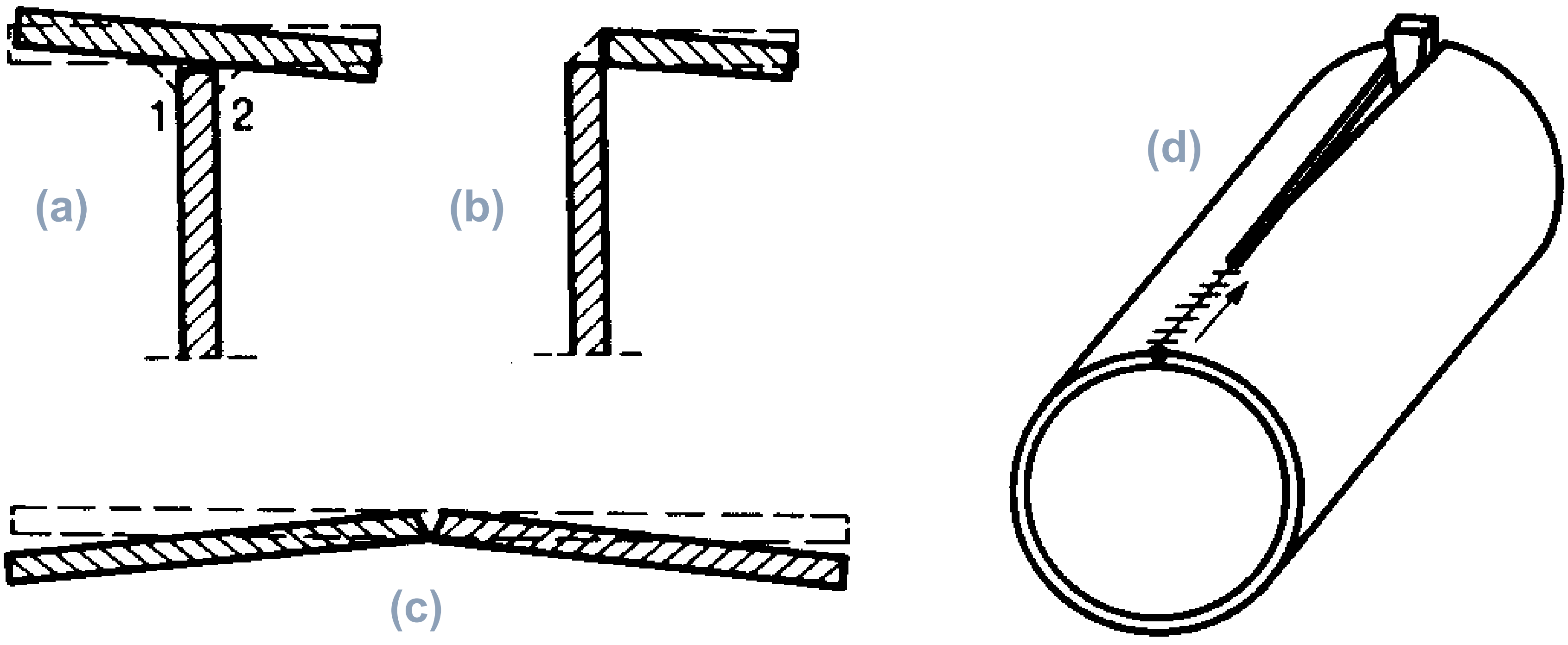
Presetting the Joints



The net effect of weld shrinkage pulls the member or connection back into proper alignment.

Reference: *Design of Weldments*, Omer W. Blodgett, 1976

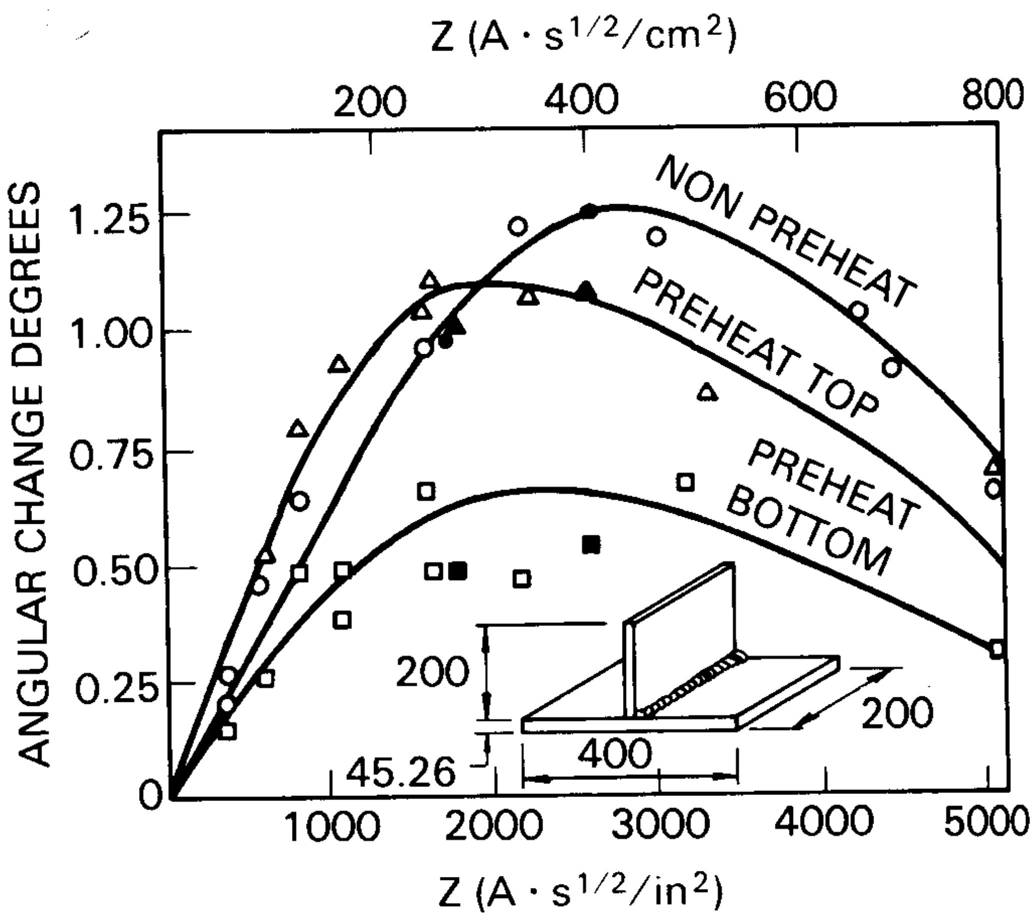
Examples of Presetting the Joints



(a) (b) Girder, (c) Plate, (d) Fixing of Groove Gap by Wedge in Single Pass Gas Welding
Pre-welding Position Traced in Solid Lines
Post-welding Position in Broken Lines

Reference: D. Radaj, *Heat Effects of Welding,* Springer-Verlag, 1992

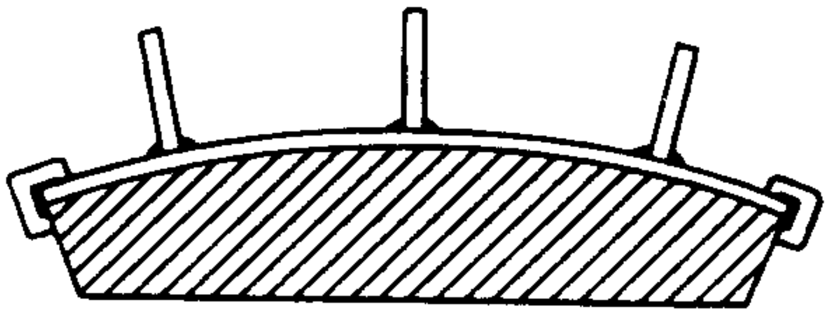
Preheat the Joint



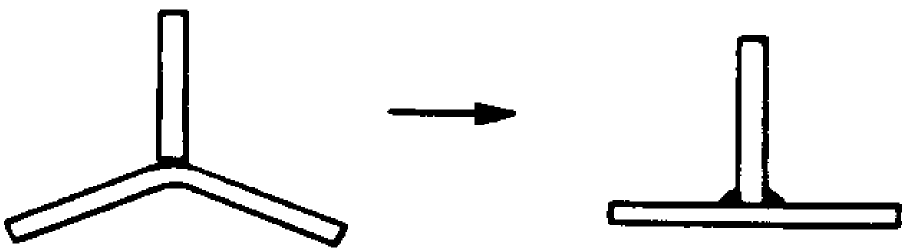
Effect of Preheat and Welding Variables on Angular Change of Steel Fillet Welded T-Joints

Reference: Kihara, H., Watanabe, M., Masubuchi, K., and Satoh, K., “Researches on Welding stress and shrinkage distortion in Japan”, 60th Anniversary Series of the Society of Naval Architects of Japan, Vol. 4, 1959

Prestrain the Joint



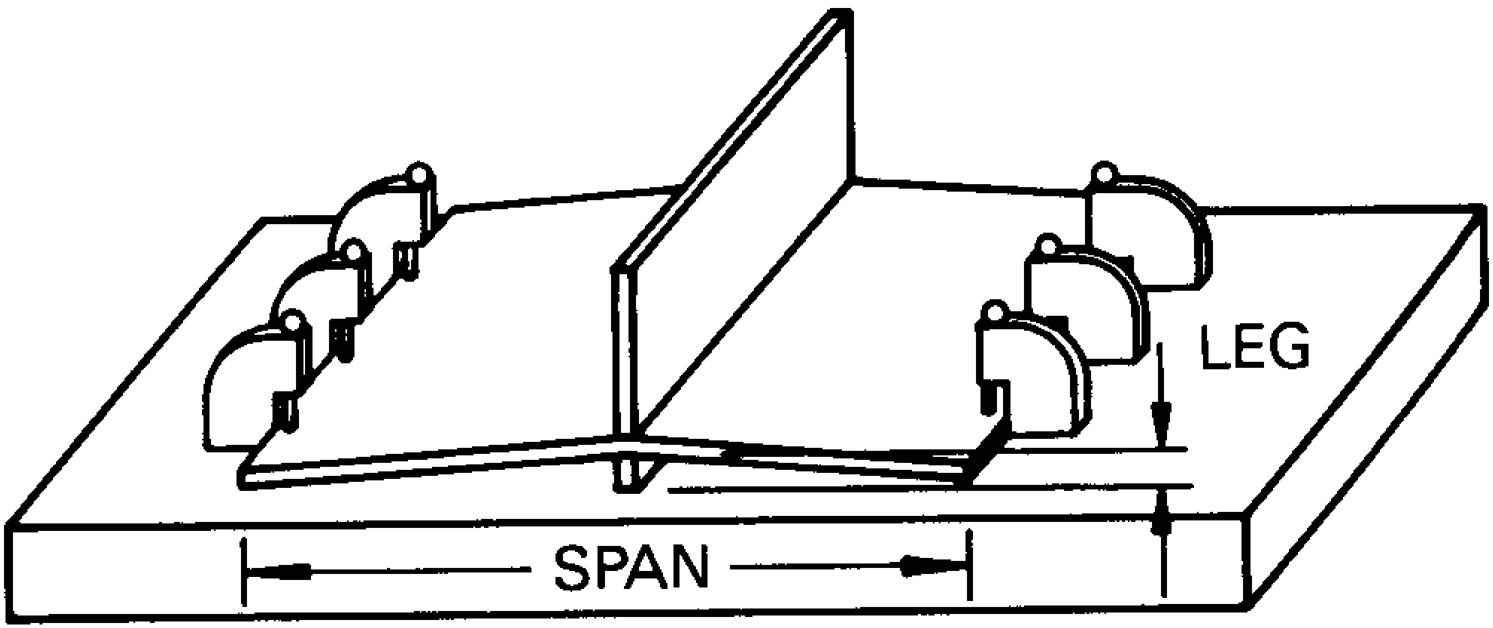
(a) Elastic Prestraining



(b) Plastic Prebending

Reference: Kumose, T., Yoshida, T., and Onoue, H, Prediction of angular distortion caused by one-pass fillet welding, The Welding Journal, 33, 945-956 (1954)

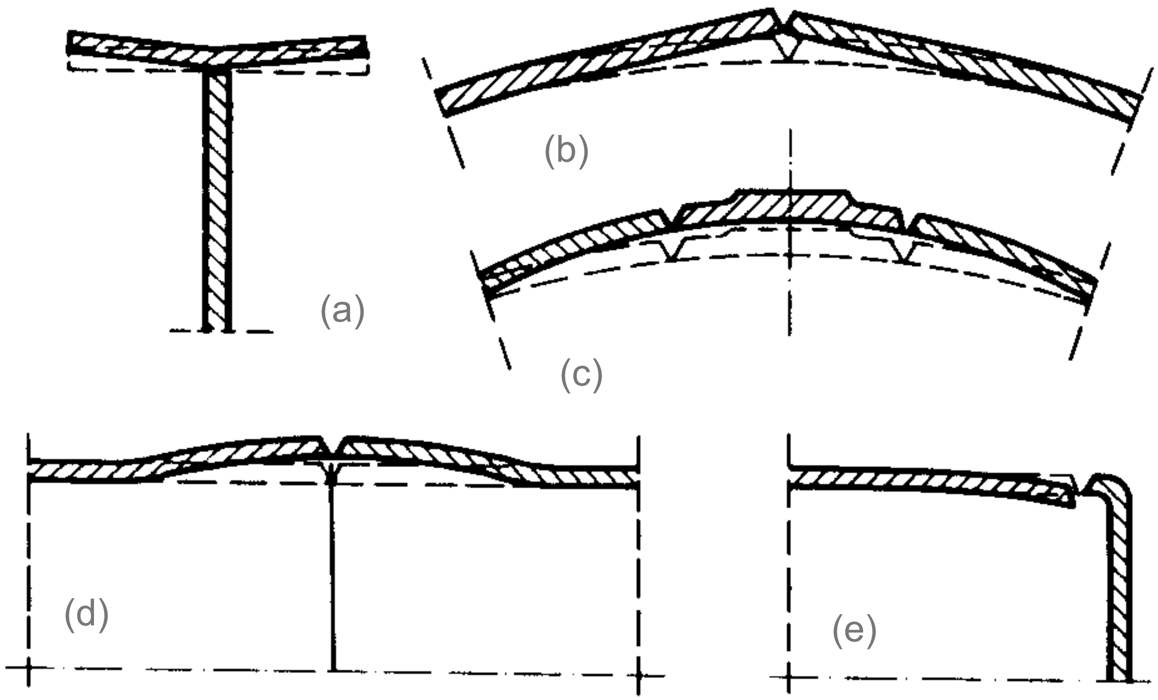
Example of Elastic Prestraining



Apparatus for Welding T-Joints Submitted to Elastic Prestrain by Bolting Down Both Free Ends

Reference: *Welding Handbook,* Volume 1, AWS, 1991

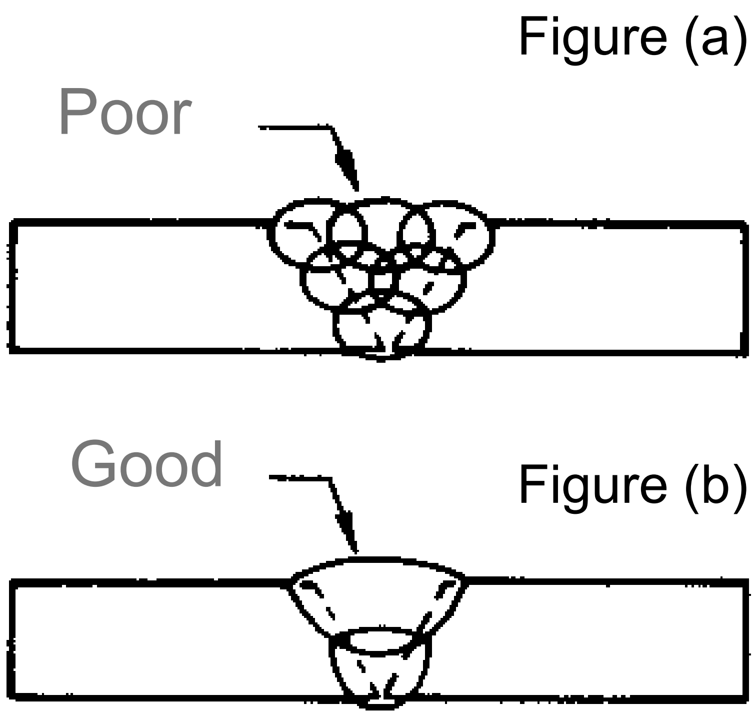
Examples of Plastic Prestraining



(a) Roof Shaping of Girder Chords
(b) Plane End Section of Cylindrical Shell
(c) Outward Bulging of Spherical Shell with Block Flange
(d) Outward Bulging of Pipe with Circumferential Weld
(e) Inward Drawing of Pipe at Plane End

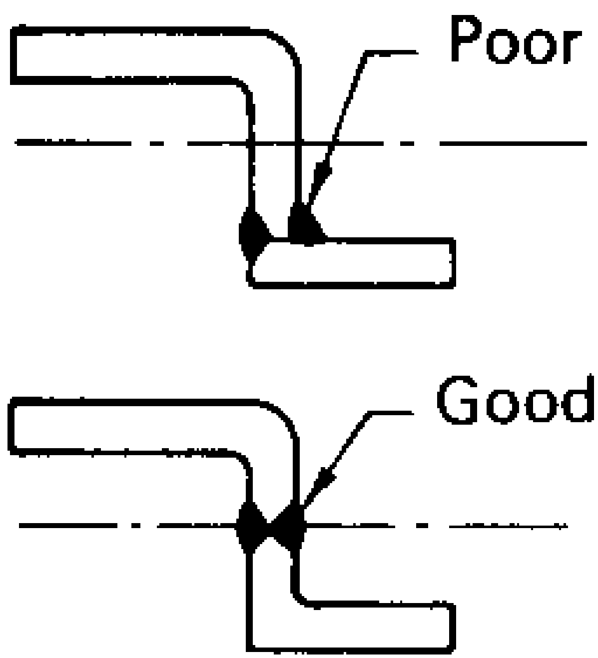
Reference: D. Radaj**,** *Heat Effects of Welding,* Springer-Verlag, 1992

Use as Few Weld Passes as Possible



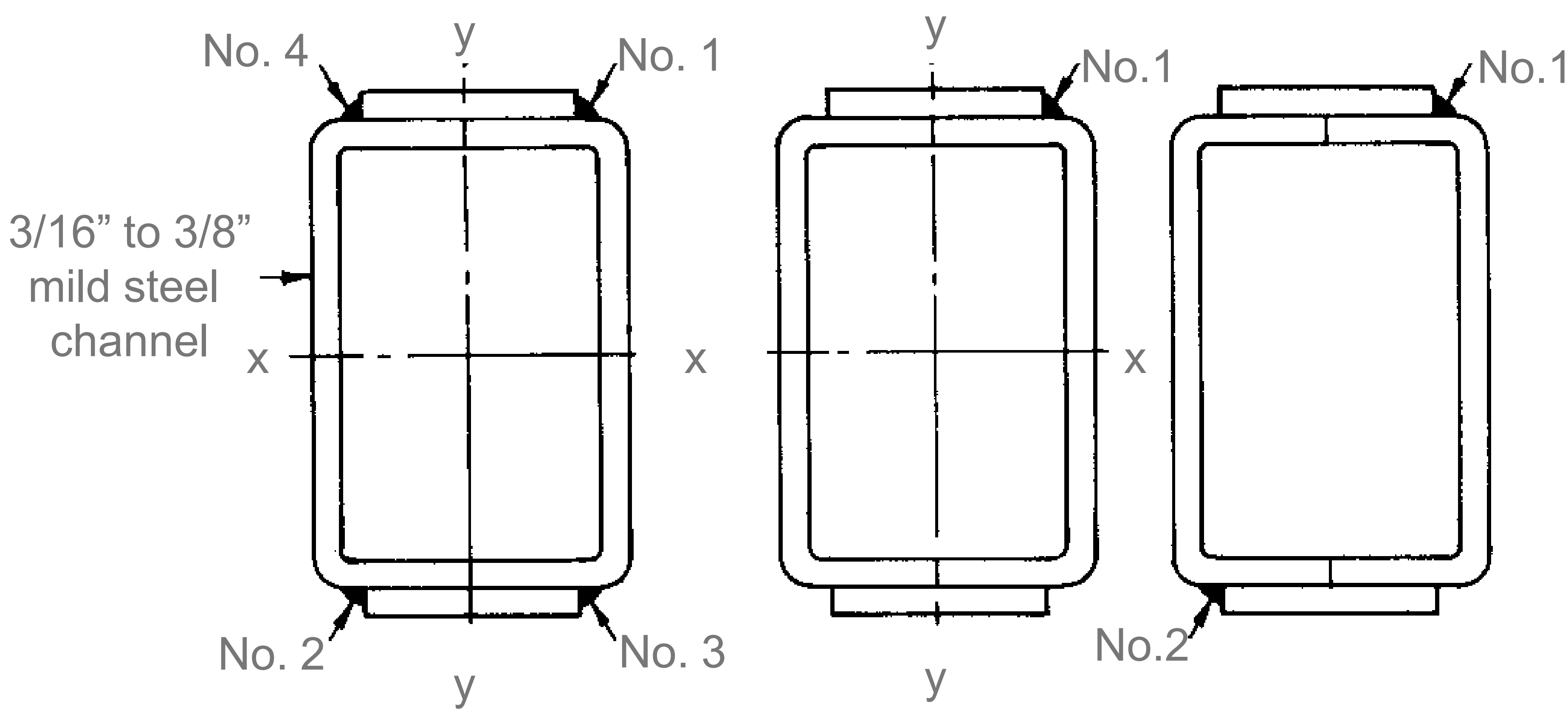
Minimum Number of Passes

Place Welds Near the Neutral Axis



Welding near Neutral Axis

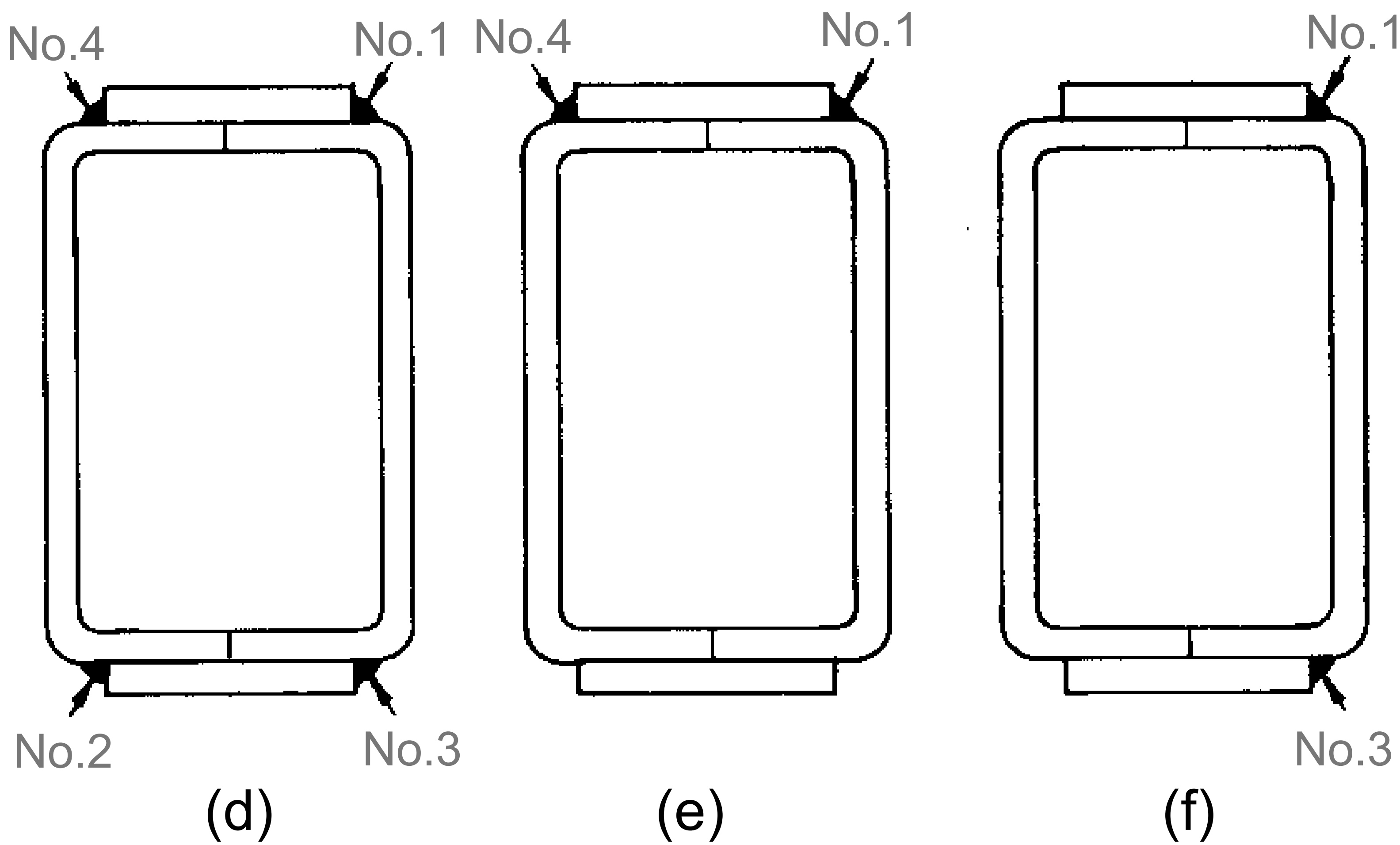
Plan the Welding Sequence
Welds are Symmetrical about Neutral Axis



(a) (b) (c)

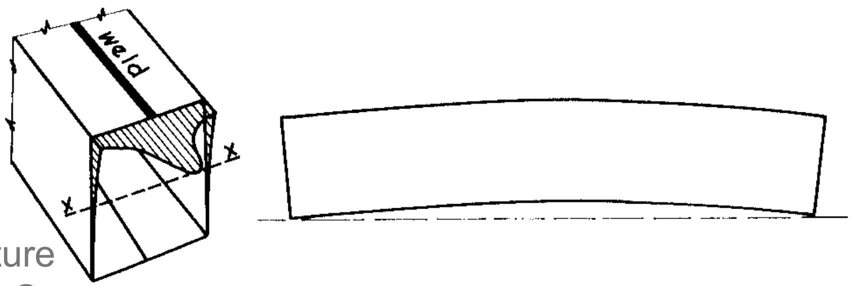
Reference: *Design of Weldments*, Omer W. Blodgett, 1976

Plan the Welding Sequence
Welds are Symmetrical about Neutral Axis



Reference: *Design of Weldments*, Omer W. Blodgett, 1976

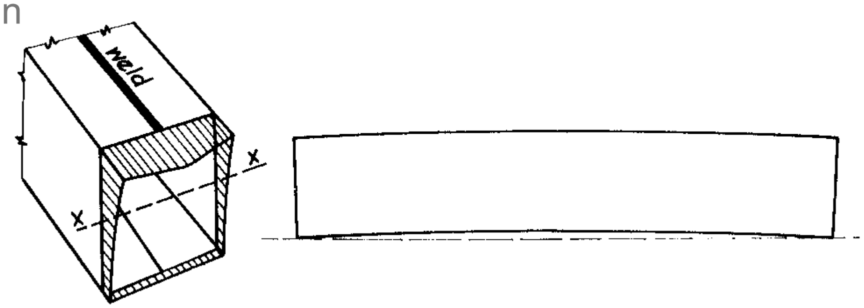
Plan the Welding Sequence
Long and Thin Box Sections



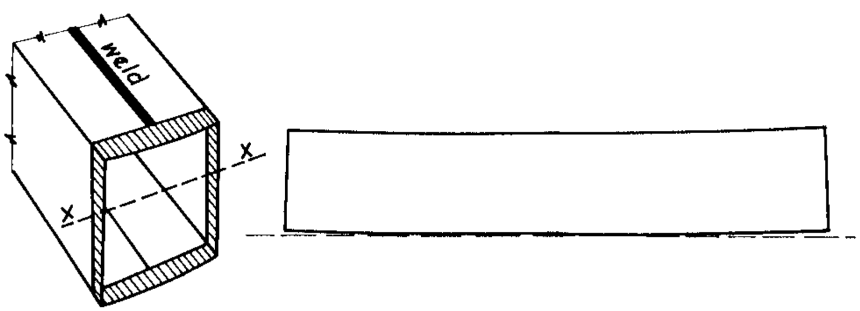
(a) During Welding, Top Expands - Center Bows Up

(Turn the Members Quickly to Protect the Weld from Cooling)

Temperature Distribution - Cross Section



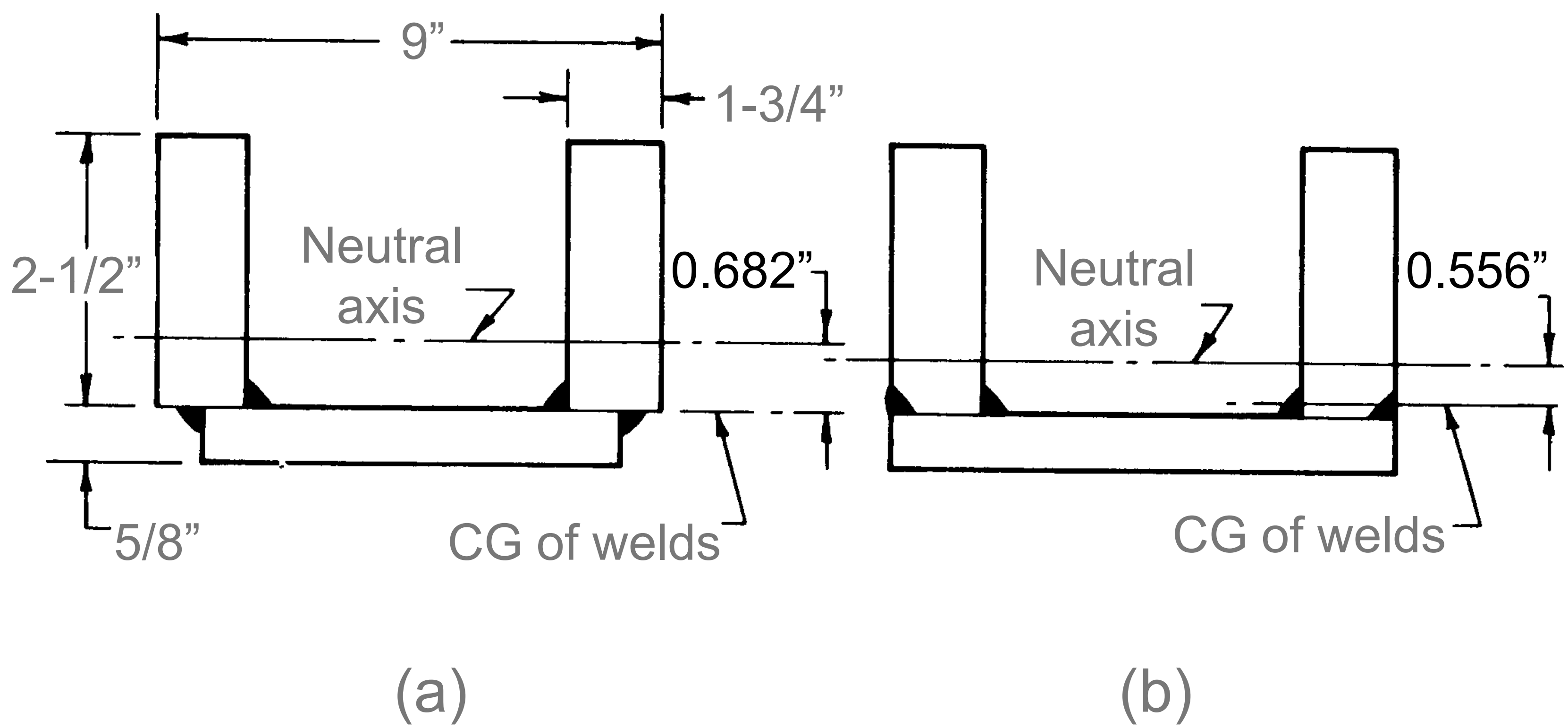
(b) Shortly after Welding - Still Bowed up Slightly



(c) After Cooled - End Very Slightly Bowed up due to Contraction of Top

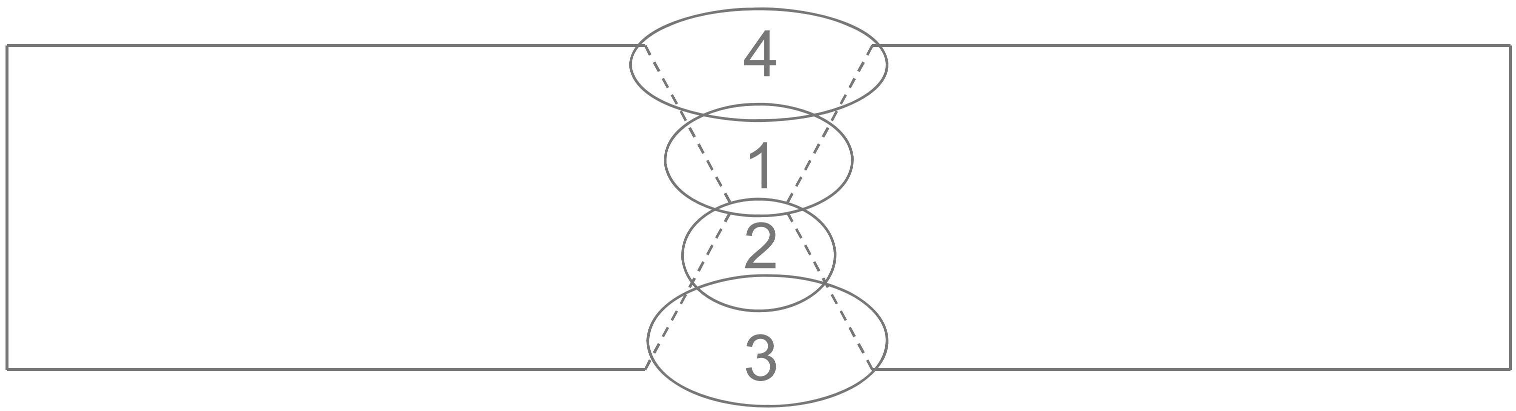
Reference: *Design of Weldments*, Omer W. Blodgett, 1976

Place Welds Near the Neutral Axis – Three -Member Column



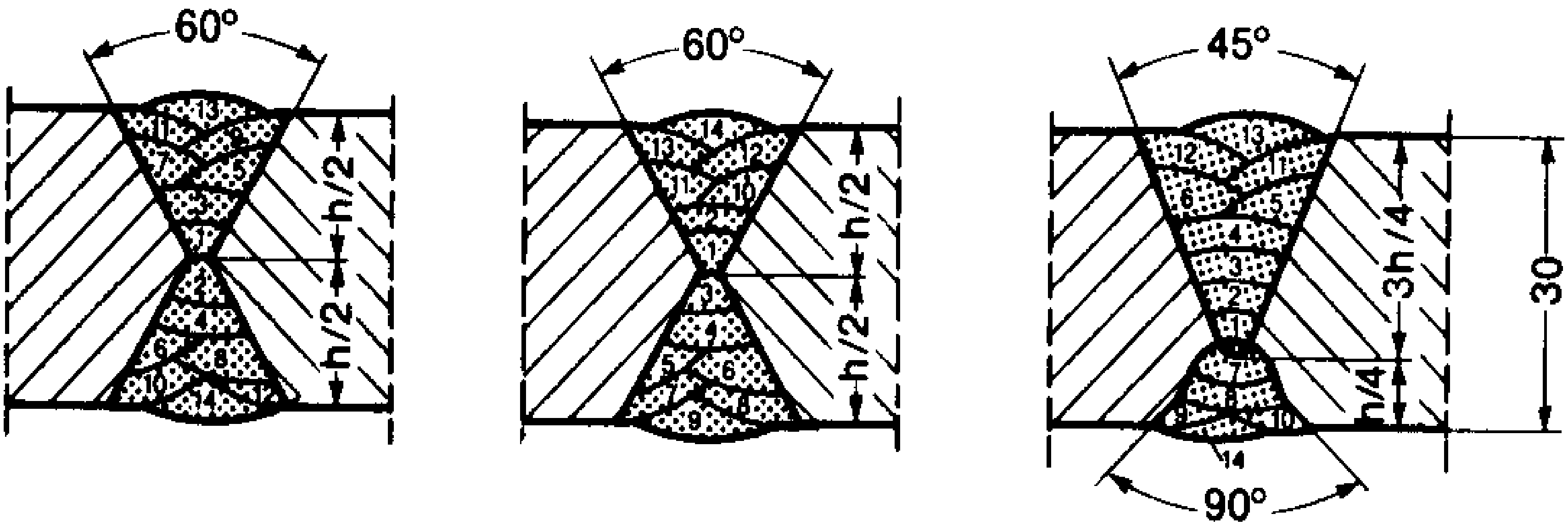
Reference: *Design of Weldments*, Omer W. Blodgett, 1976

Plan the Welding Sequence – Multi-Layer Welding



An Example of a Double V-Groove Butt Joint. Suitable Welding Sequence in Multi-layer Welding can Reduce Angular Distortion

Plan the Welding Sequence – Multi-Layer Welding

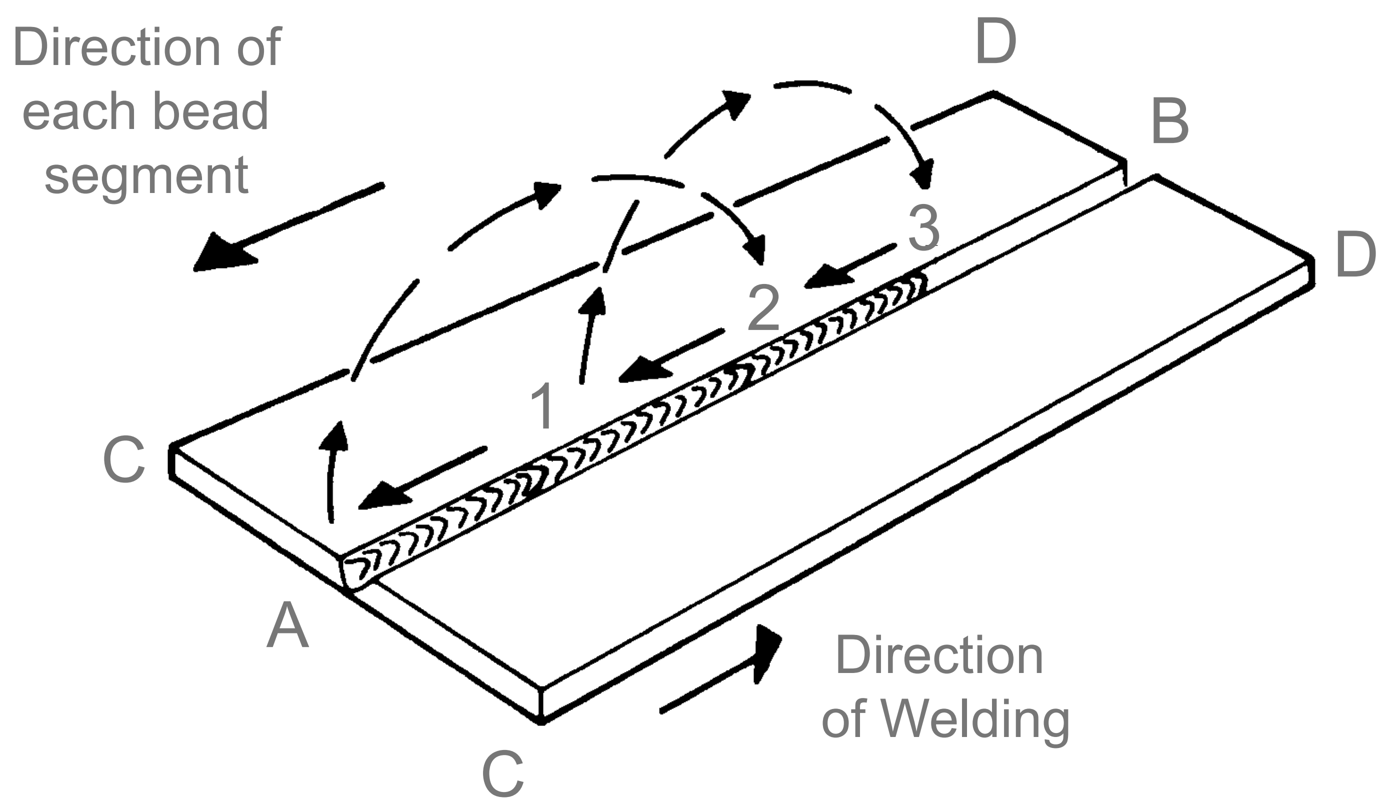


(a) (b) (c)

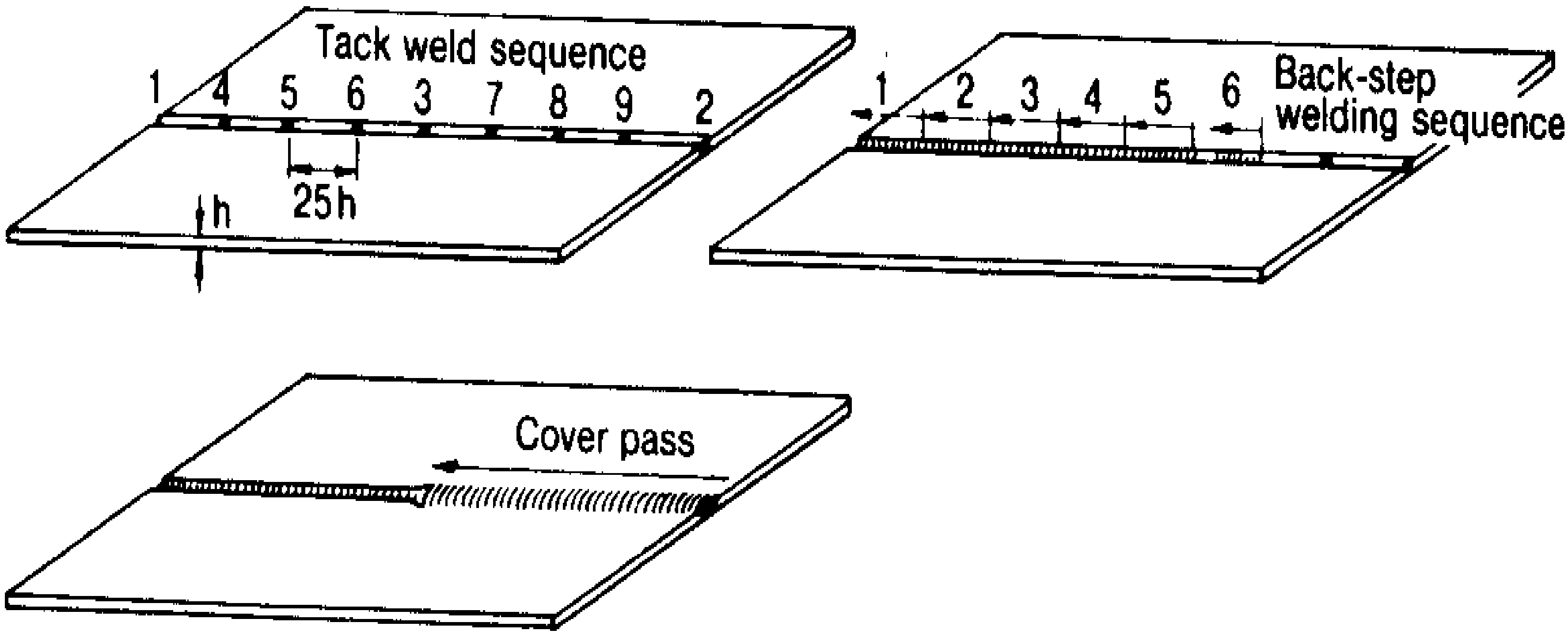
Reduction of Angular Distortion by Alternating Weld Pass Deposition in Double-V Groove

Reference: D. Radaj, *Heat Effects of Welding,* Springer-Verlag, 1992

Plan the Welding Sequence – Backstep Welding



Plan the Welding Sequence – Backstep Welding

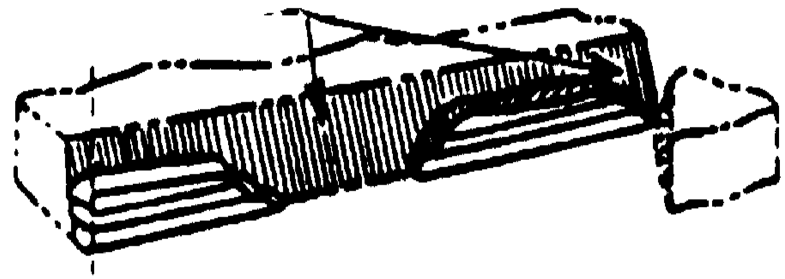


Reduction of Transverse Shrinkage as well as Groove Gap Distortion by Back-Step Welding: Tack Weld Sequence (a), Back-Step Welding Sequence in First Layer (b) and Cover Pass (c)

Reference: D. Radaj, *Heat Effects of Welding,* Springer-Verlag, 1992

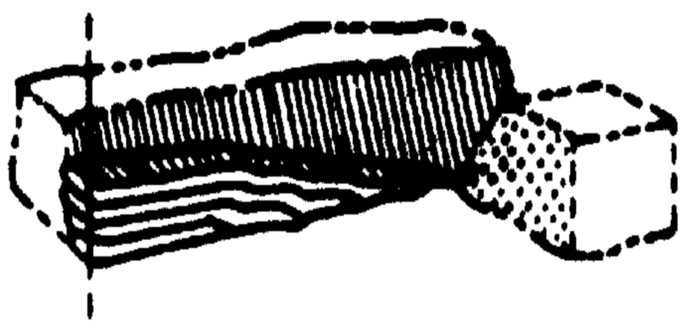
Distortion Control by Welding Sequence – Welding Sequences

(A) Backstep Sequence



(B) Block Sequence

(C) Built-up Sequence



(D) Cascade Sequence

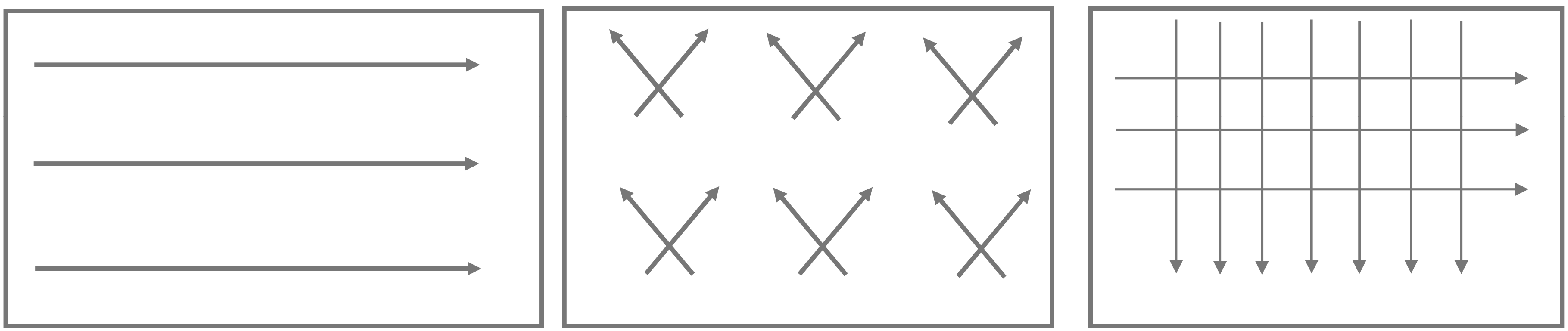
Reference: K. Masubuchi, *Analysis of Welded Structure,* Pergamon Press

Methods of Removing Distortion – Flame (Thermal) Straightening

- Line heating
- Pine-needle heating
- Heating in cross section
- Spot heating
- Triangular heating
- Red-hot heating

Reference: *Analysis of Welded Structures*, Koichi Masubuchi

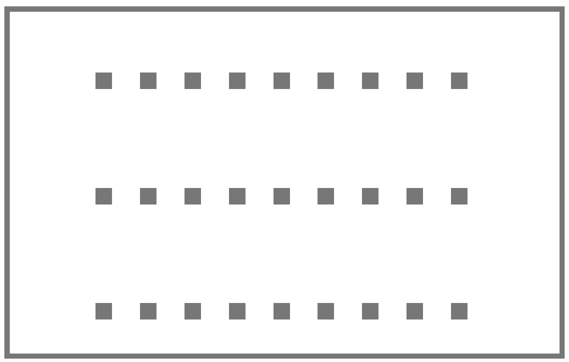
Methods of Removing Distortion – Flame (Thermal) Straightening



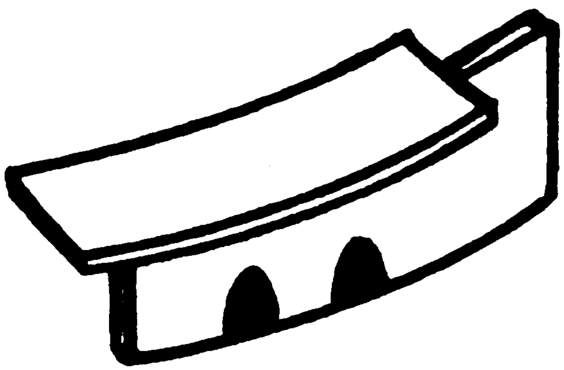
Line Heating | Pine-needle Heating | Heating in Cross Directions

Reference: *Analysis of Welded Structures*, Koichi Masubuchi

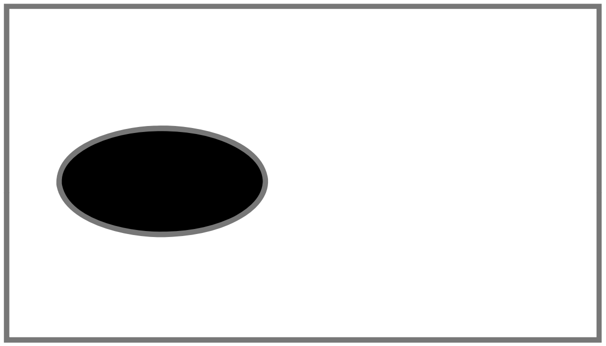
Methods of Removing Distortion – Flame (Thermal) Straightening



Spot Heating



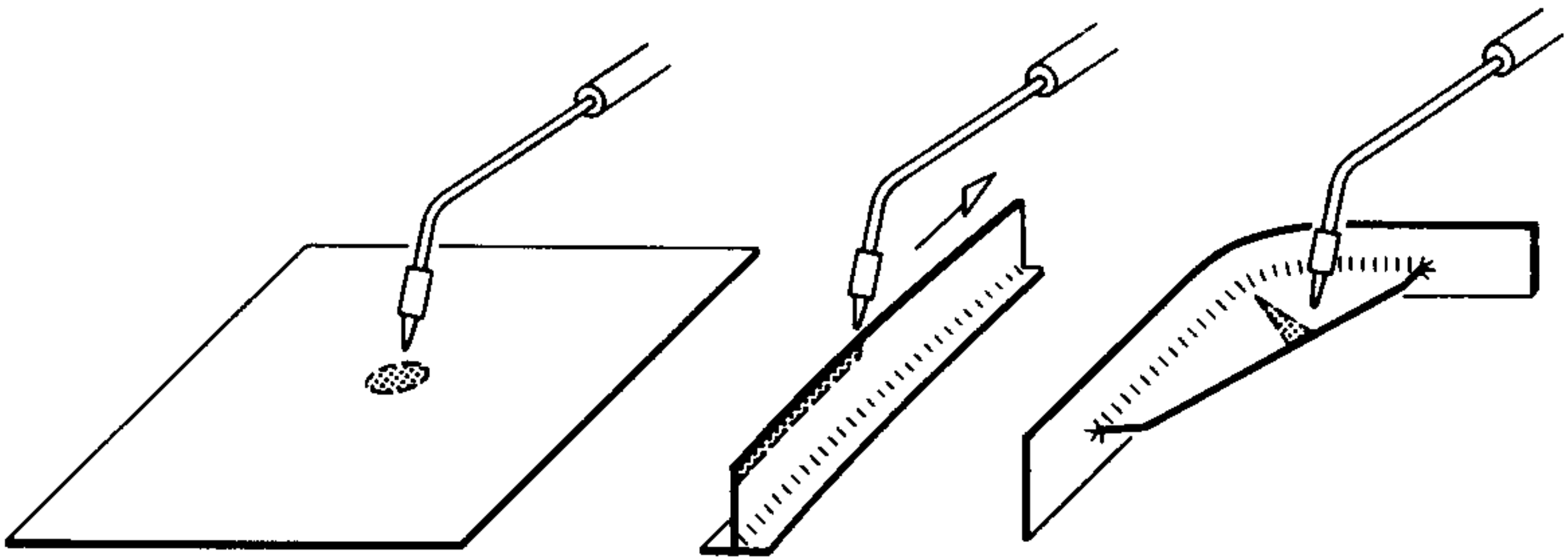
Triangular Heating



Red-hot Heating

Reference: *Analysis of Welded Structures*, Koichi Masubuchi

Methods of Removing Distortion – Flame (Thermal) Straightening

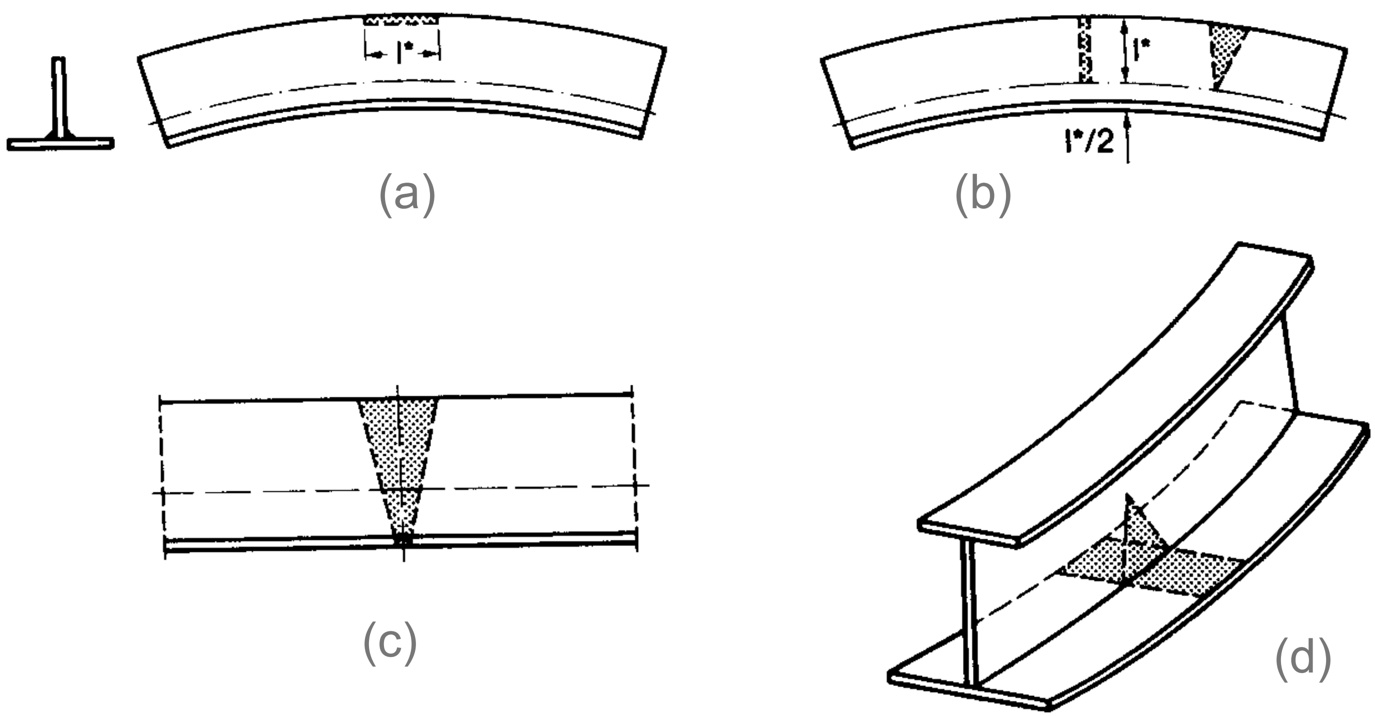


(a) Spot Shape (b) Strip Shaped (c) Wedge Shaped

Application of Flame Straightening

Reference: D. Radaj, *Heat Effects of Welding,* Springer-Verlag, 1992

Methods of Removing Distortion – Flame (Thermal) Straightening



Flame Straightening by Means of Heat Strips and Heat Wedges in Different Arrangement on Bending-Distorted Girders

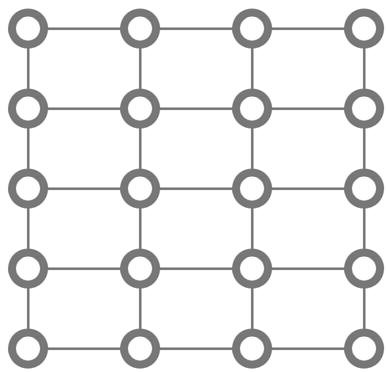
Reference: Vinokurov, V. A., *Welding stresses and distortion,* Wetherby:British Library 1977

Fracture and Fatigue

Module 4C

Linear Elastic Fracture Mechanics

For a perfect solid, the tensile strength σ_{T} can be related to Young's modulus for the material E.



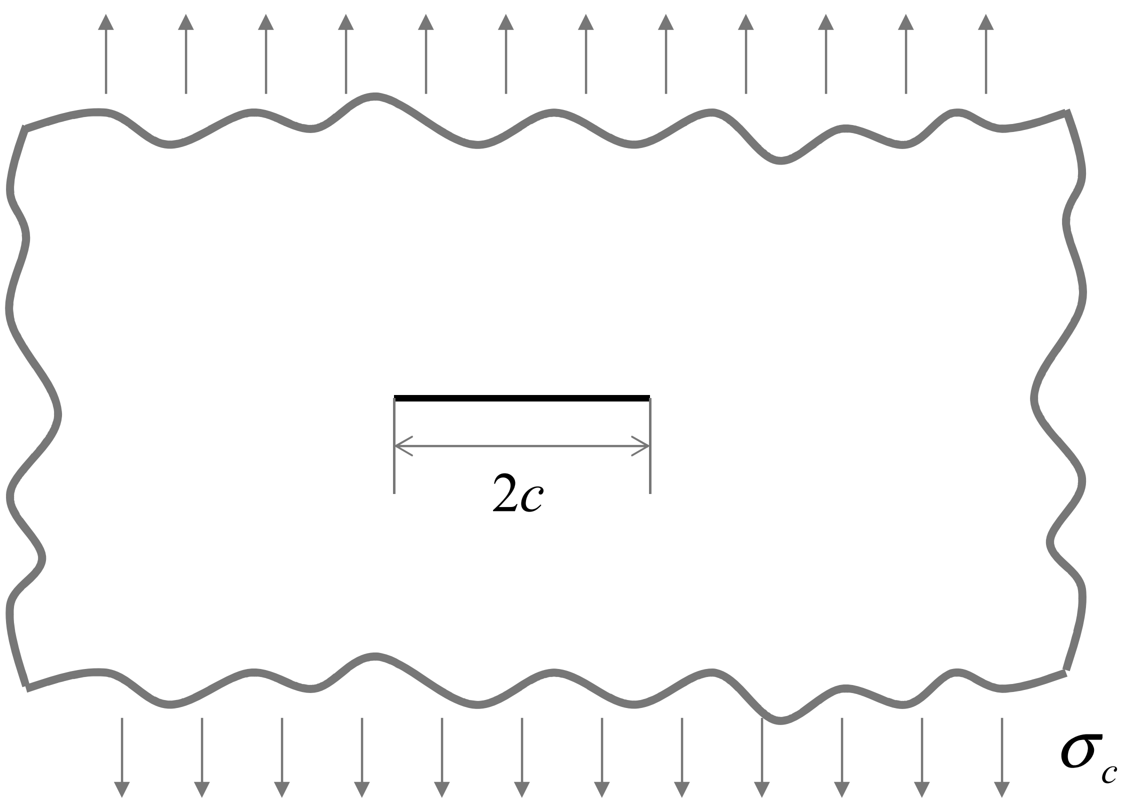
$$\sigma_T = \frac{E}{10} \text{ to } \frac{E}{20}$$

For glass, this would be $\sigma_T = 10^6$ psi

while actually it is 5×10^3 to 10^5 psi

Brittle Fracture

- Griffith – glassy materials contain crack like defects which act as stress raisers.



$$\sigma_c = \sqrt{\frac{2E\gamma_s}{\pi c}}$$

γ_s = surface energy of fracture

Brittle Fracture

For long sharp cracks

$$SCF \cong 1 + 2\sqrt{\frac{c}{a}} \cong 2\sqrt{\frac{c}{a}}$$

For $\sigma_T = \frac{E}{10}$, one gets

$$\sigma_c \cong \frac{E}{20}\sqrt{\frac{a}{c}} \rightarrow \text{gives similar results to Griffith's Criterion}$$

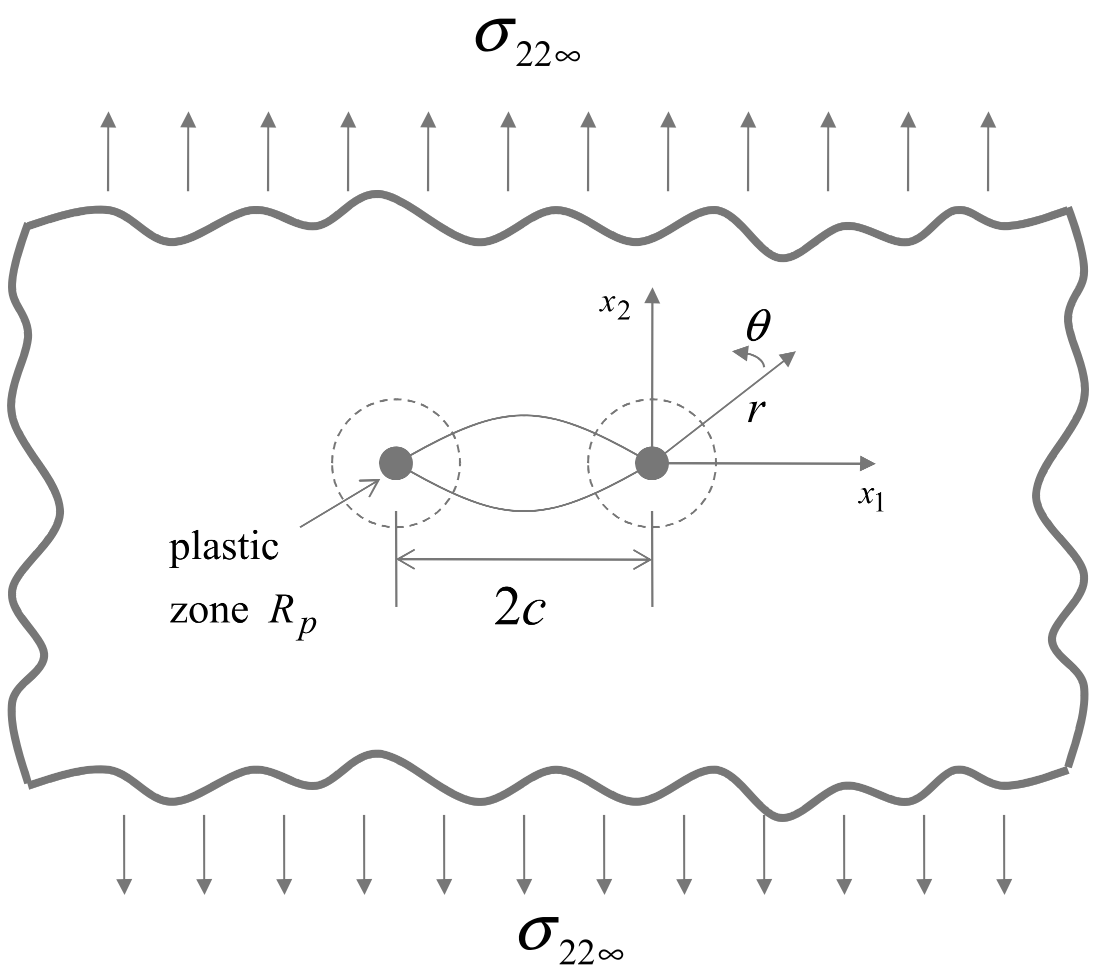
Back calculating crack lengths in glasses,

one gets lengths of order 25 to 2500

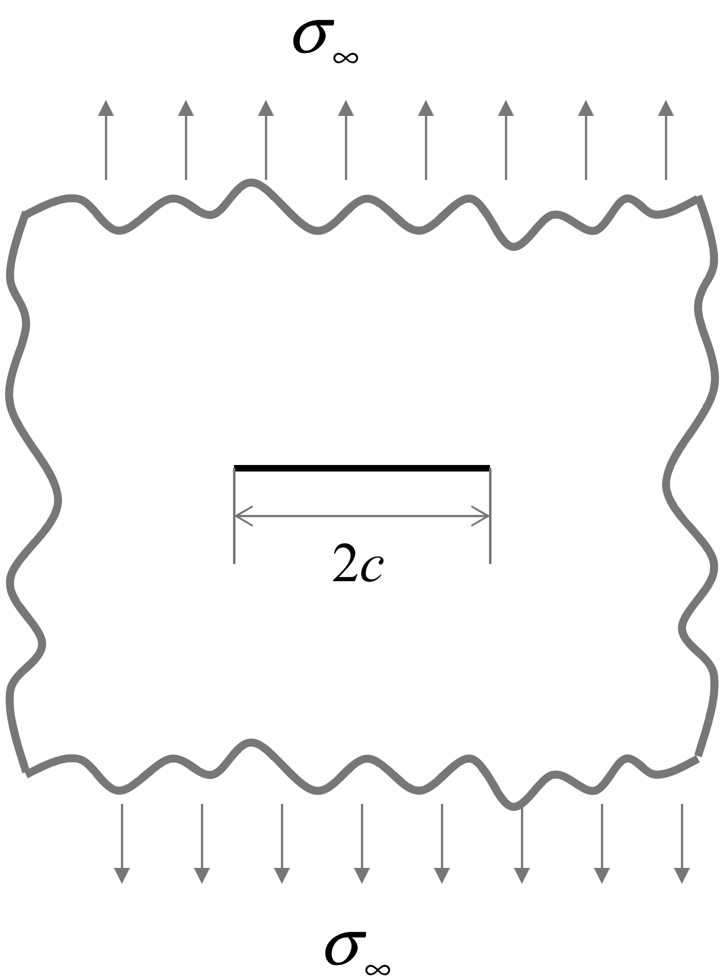
atomic distances or 100 - 10,000 A^o

Linear Elastic Fracture Mechanics

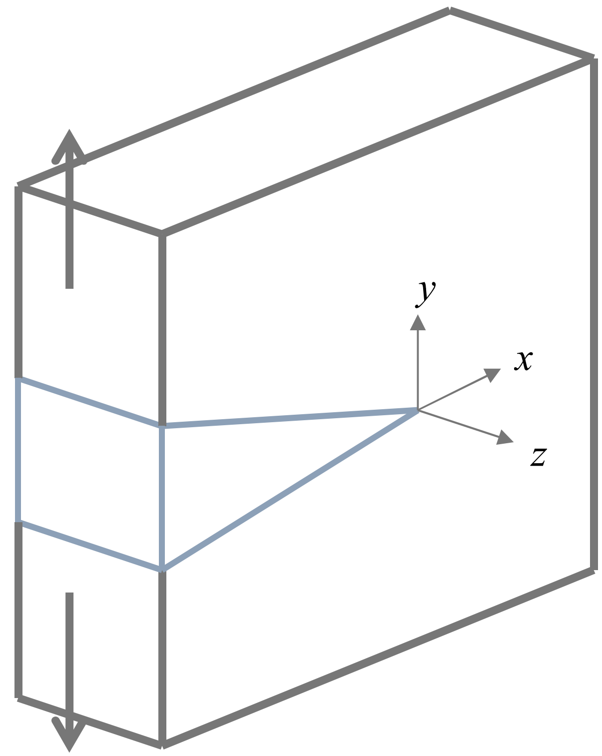
- Mode I



Linear Elastic Fracture Mechanics

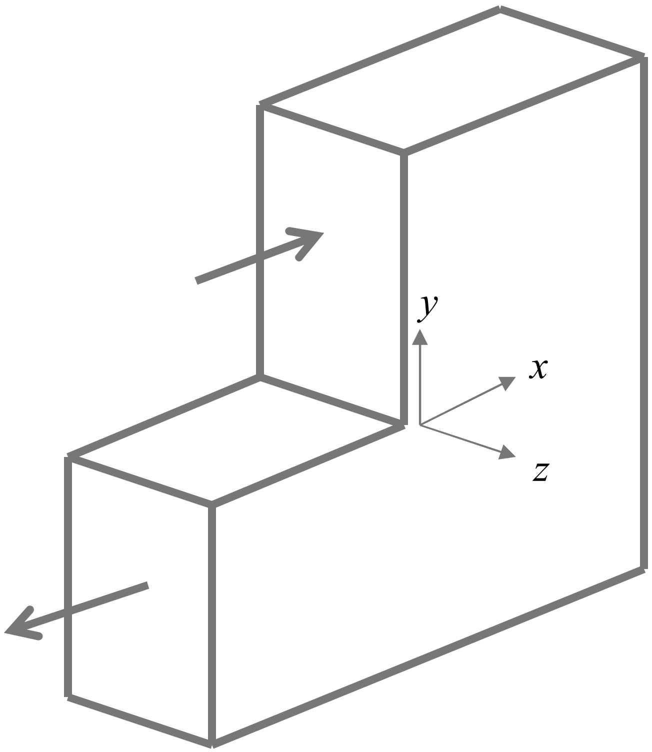


$$K_I = \sigma_\infty \sqrt{\pi c}$$

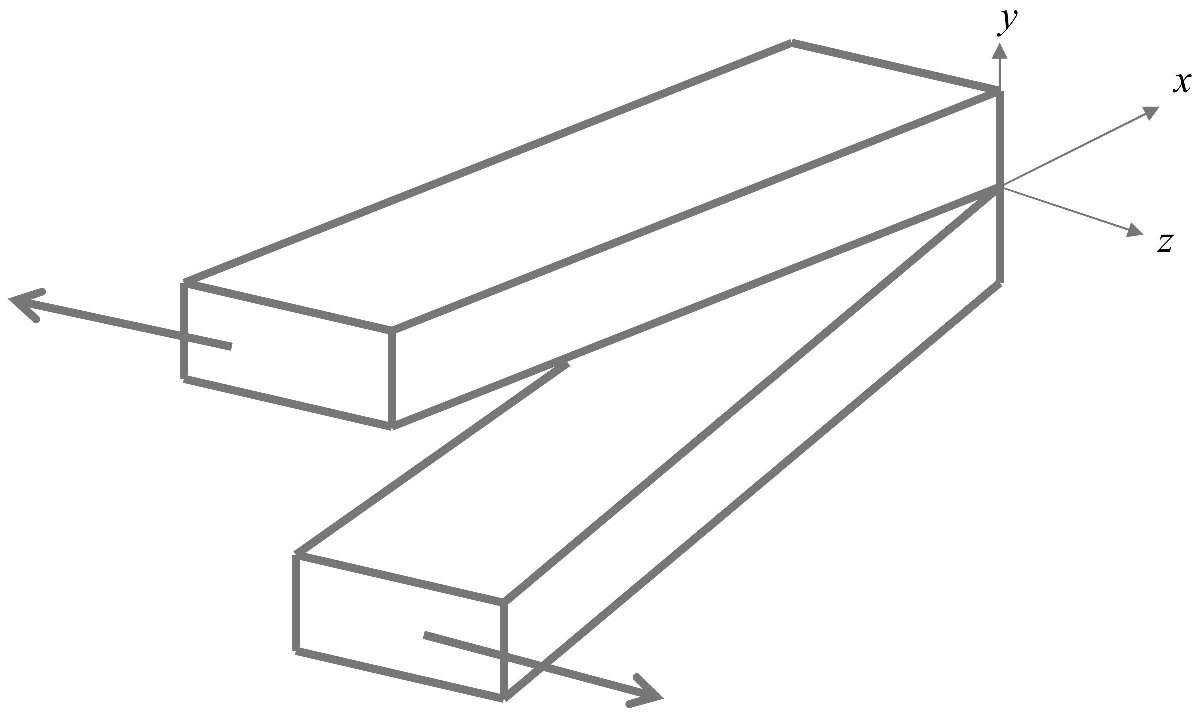


For r=0 stresses are infinite!
Is this realistic?

Linear Elastic Fracture Mechanics



Mode II



Mode III

Stress Intensity Factors

Stress intensity factor is used to find the stress distribution and magnitude near the crack tip. It is a function of:

σ = applied stress

c = half crack length (full crack length for edge cracks)

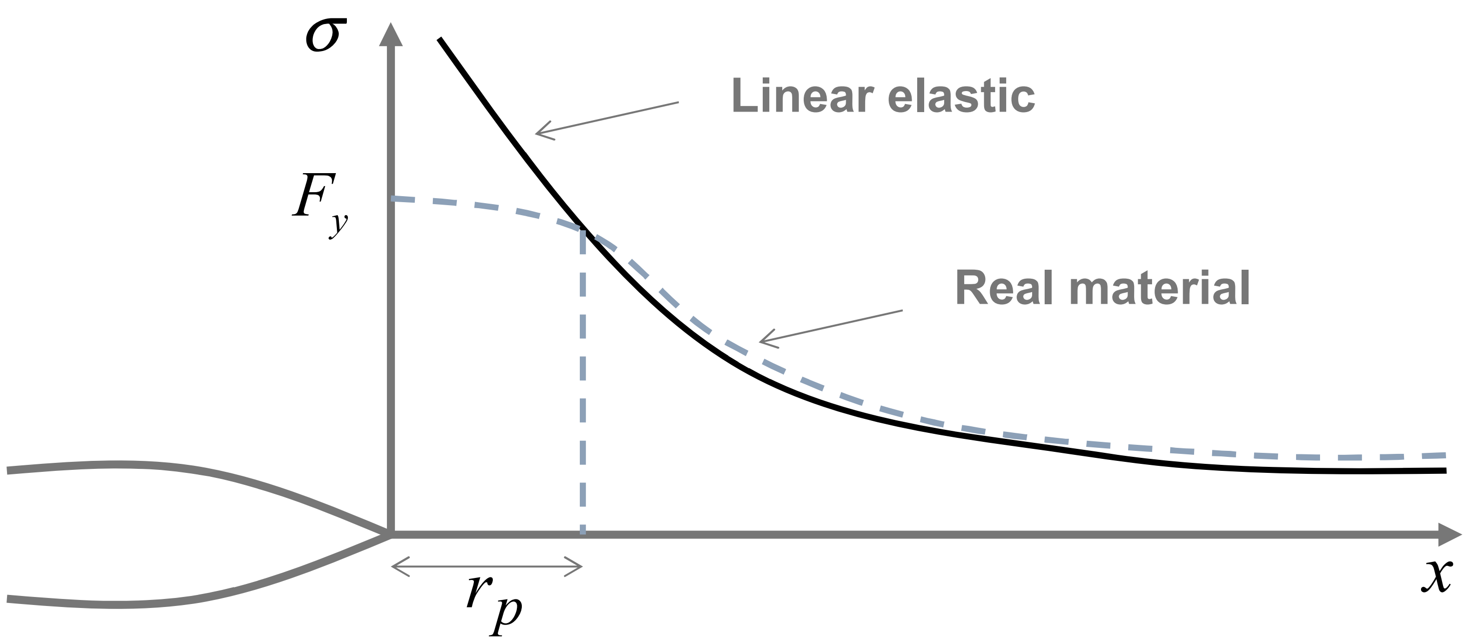
w= characteristic dimension for the part

$$K(\sigma, c, w) = f\left(\frac{c}{w}\right)\sigma\sqrt{\pi c}$$

Determined analytically or experimentally as well as by finite element analysis.

Fracture Toughness (Kc)

- Kc is a material property which indicates the stress intensity factor above which crack extension will occur
- KIC (the plane strain value of Kc) is a linear elastic facture mechanics parameter which can be used for brittle fracture
  - For real materials, some plastic deformation will occur near the crack tip.



Fracture Toughness

For plane stress, the size of the plastic zone is found from

$$F_y = \frac{K_I}{\left(\sqrt{2\pi\, r_p}\right)} \cos\left(\frac{\theta}{2}\right)\left[\left(1+\sin\frac{\theta}{2}\right)\left(\sin\frac{\theta}{2}\right)\right]$$

where for $\theta = 0^0$

$$F_y = \frac{K_I}{\left(\sqrt{2\pi\, r_p}\right)} \qquad r_p = \frac{1}{2\pi}\left(\frac{K_I}{F_y}\right)^2$$

For plane strain,

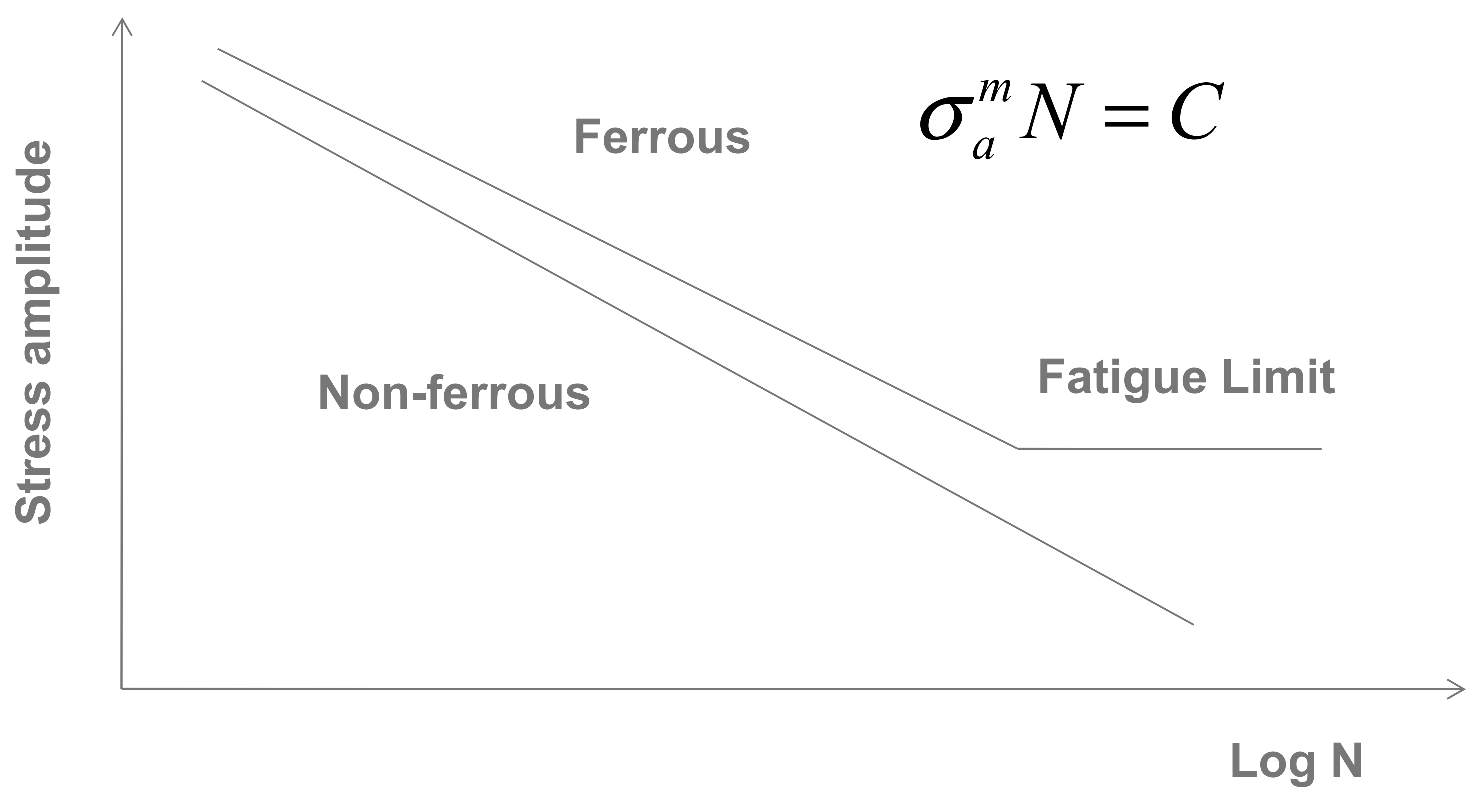
$$r_p = \frac{1}{6\pi}\left(\frac{K_I}{F_y}\right)^2$$

For LEFM the size of the plastic zone must be small

Fatigue

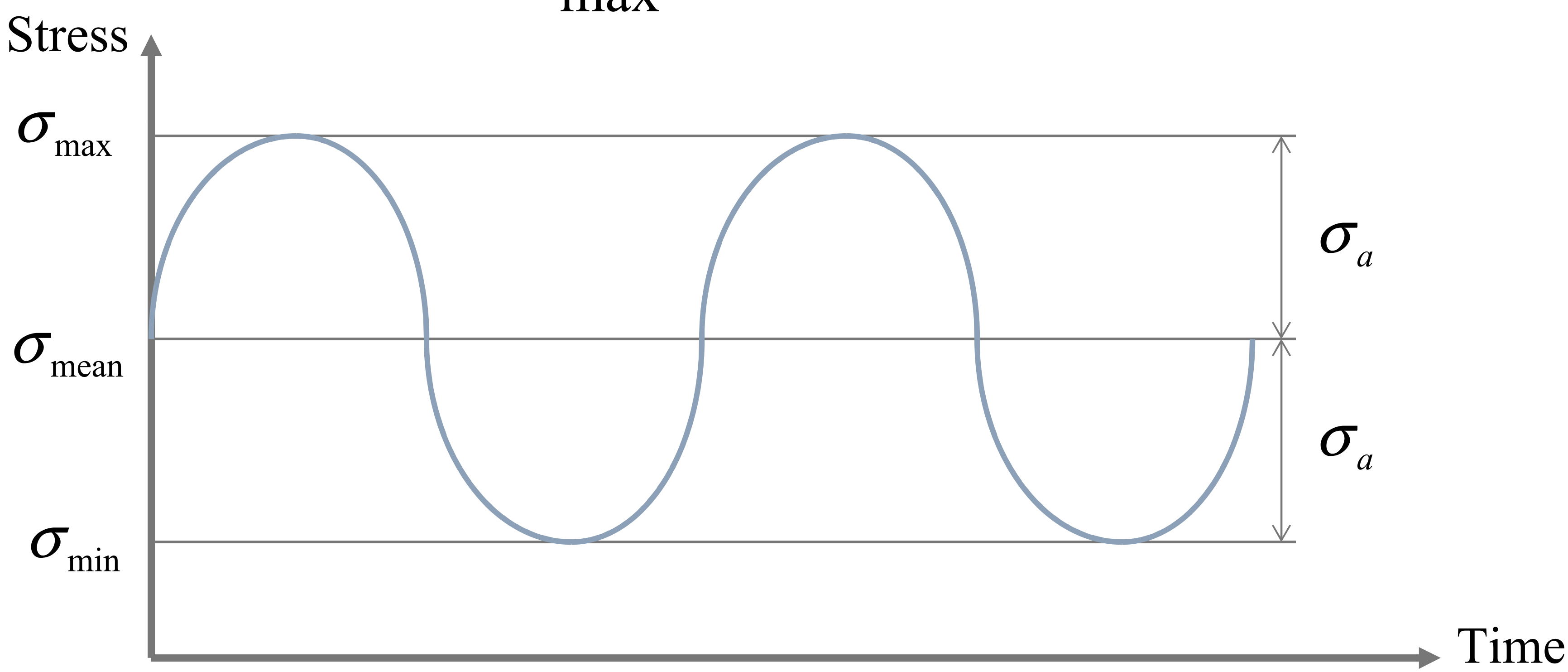
- Fatigue failure resulting from cyclic deformation with large plastic strain amplitude is called low cycle fatigue
  - Failure usually occurs in ten to several hundred cycles
- Fracture resulting from many thousands of stress cycles below the elastic limit are called high cycle fatigue
- Phases for Fatigue Failure
  - Crack initiation – stress concentrations at grain boundaries or flaws
  - Crack propagation – The crack propagates on every cycle of loading
  - Fracture – crack long enough for fracture to occur when maximum stress is reached

S-N Curve


Ferrous
$\sigma_a^m N = C$
Fatigue Limit
Non-ferrous
Stress amplitude
Log N

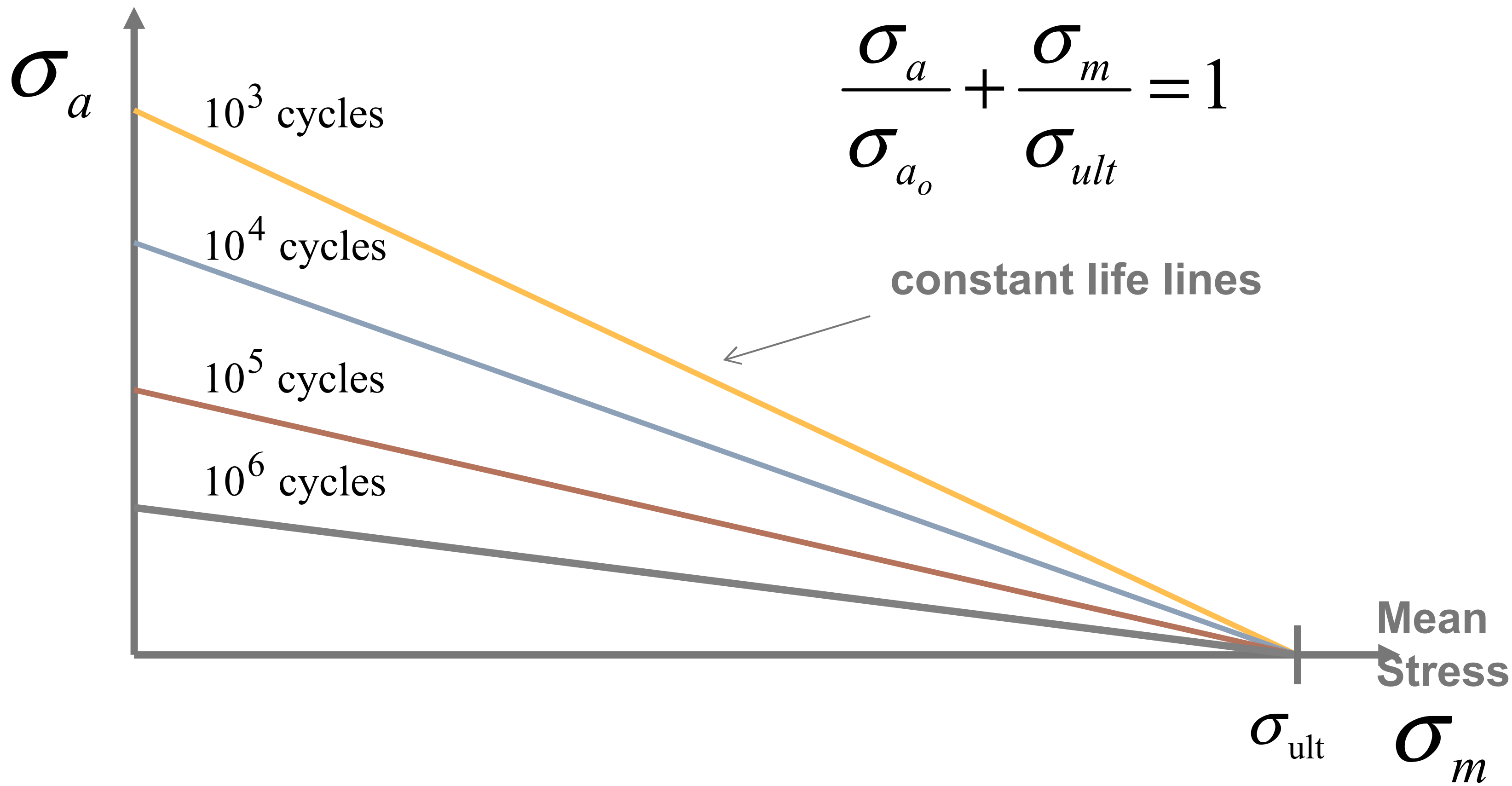
Nonzero Mean Stress

Stress ratio $R = \dfrac{\sigma_{\min}}{\sigma_{\max}}$ **Tension-compression** $R = -1$

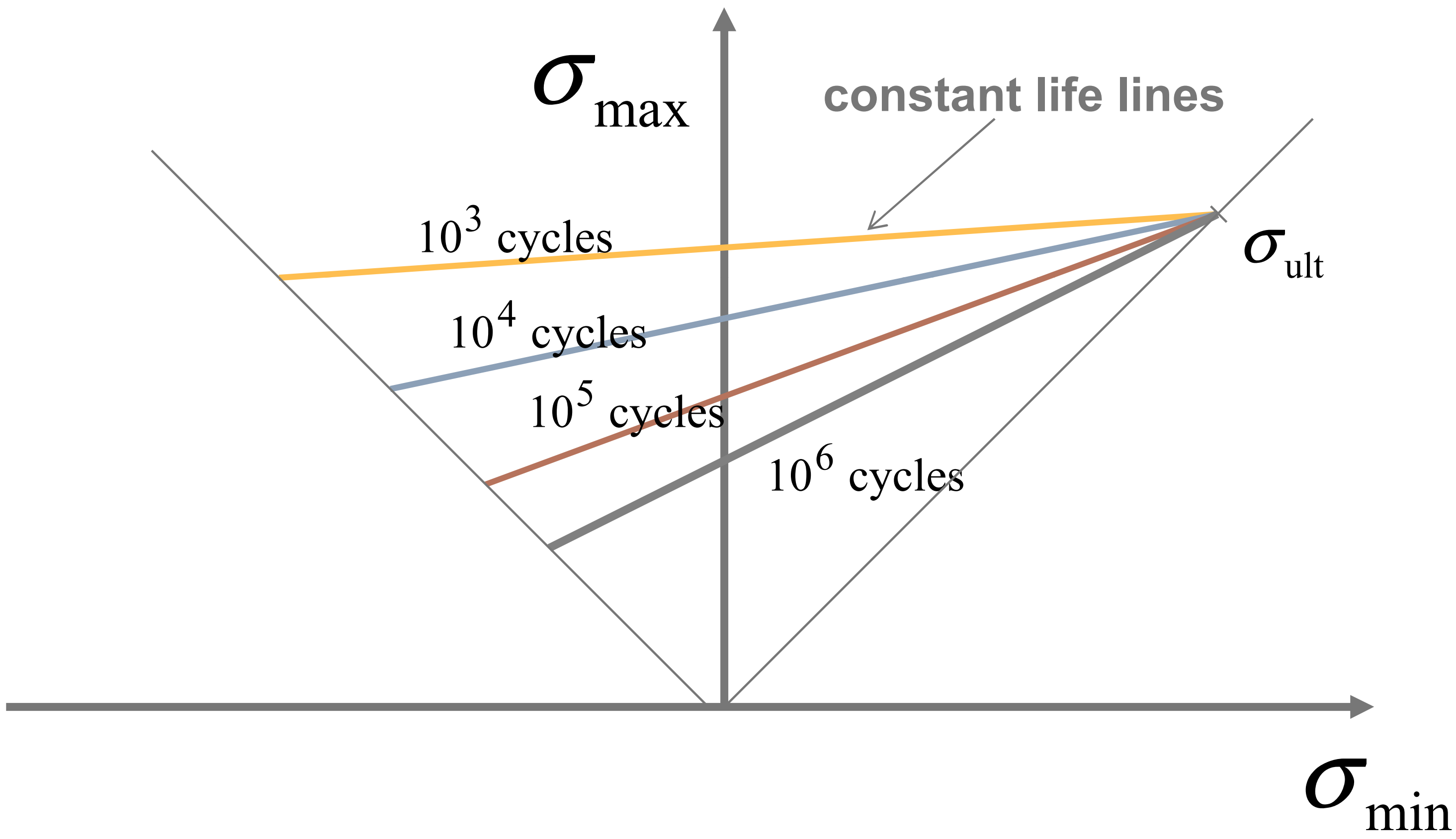


Goodman Diagram

$$\frac{\sigma_a}{\sigma_{a_o}} + \frac{\sigma_m}{\sigma_{ult}} = 1$$



Goodman Diagram



Fatigue With Varying Stress Amplitude – Miner's Rule

Miner's Rule – each cycle uses a fraction of the fatigue life.

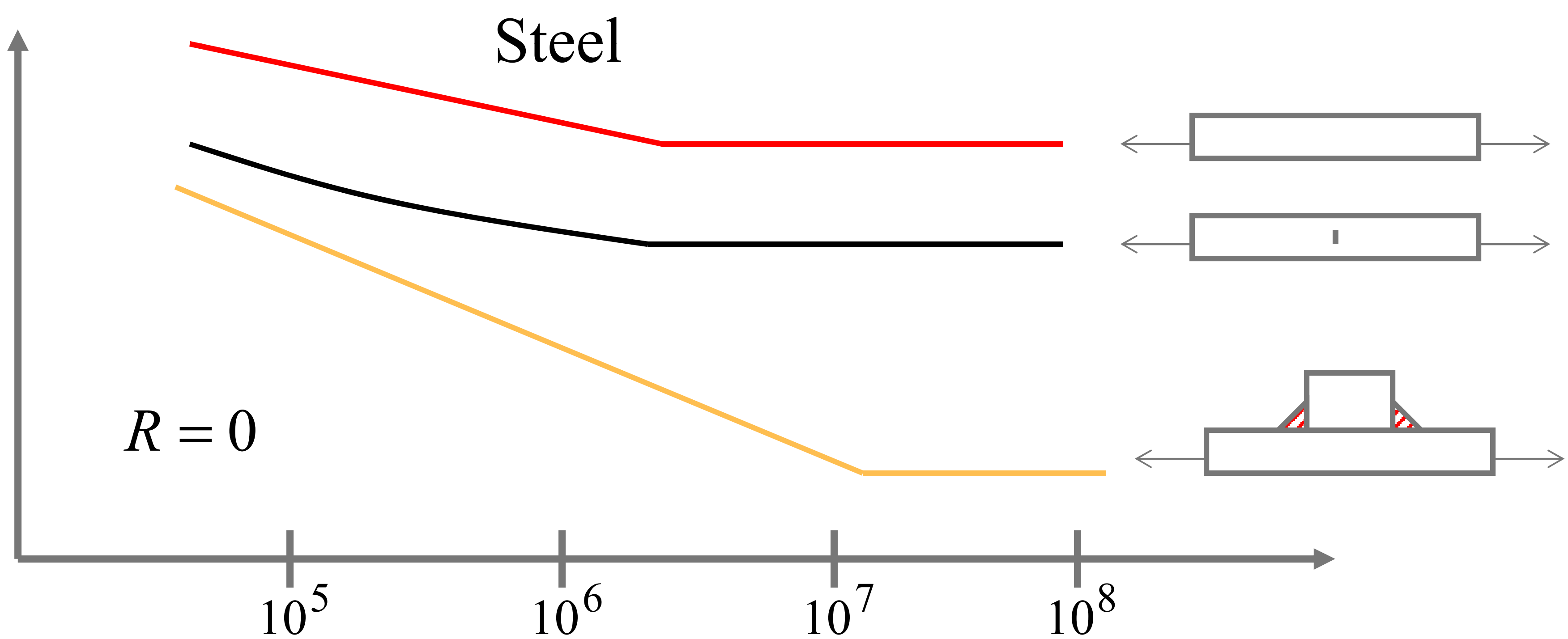
$$\sum_{i=1}^{k} \frac{n_i}{N_i} = 1$$

For fully reversible tension-compression loading from S-N curve one gets,

$$\sum_{i=1}^{k} \frac{n_i}{C} \sigma_i^m = 1$$

Fatigue of Welded Joints

- The presence of welded member usually results in drastic reduction in fatigue life or stress
- Causes: Stress Concentrations – generally a weld introduces stress concentrations



Joint Design

Module 4D

Common Design Requirements

- Proper Weld Design to Meet Following Requirements
  - Strength against rupture (excessive yielding)
  - Toughness against fracture, especially under dynamic or impact loading (brittle fracture)
  - Ductility (ability to stretch) to prevent welding-induced cracking or cracks due to excessive deformation
  - Fatigue resistance against cyclic loading

Essential and Related Design Factors

- Proper Weld Design to Meet Following Requirements
  - Materials
    - Base Metal (e.g. ASTM A36)
    - Filler Metal (e.g. AWS A5.1)
  - Joints/Welds
  - Welding Process(es)/Procedure Qualification
    - Joint Thickness
    - Pipe Outside Diameter
    - Welding Position
  - Welder Qualification (per qualified procedure)
  - Workmanship (including distortion control, heat treatment)
  - Inspection

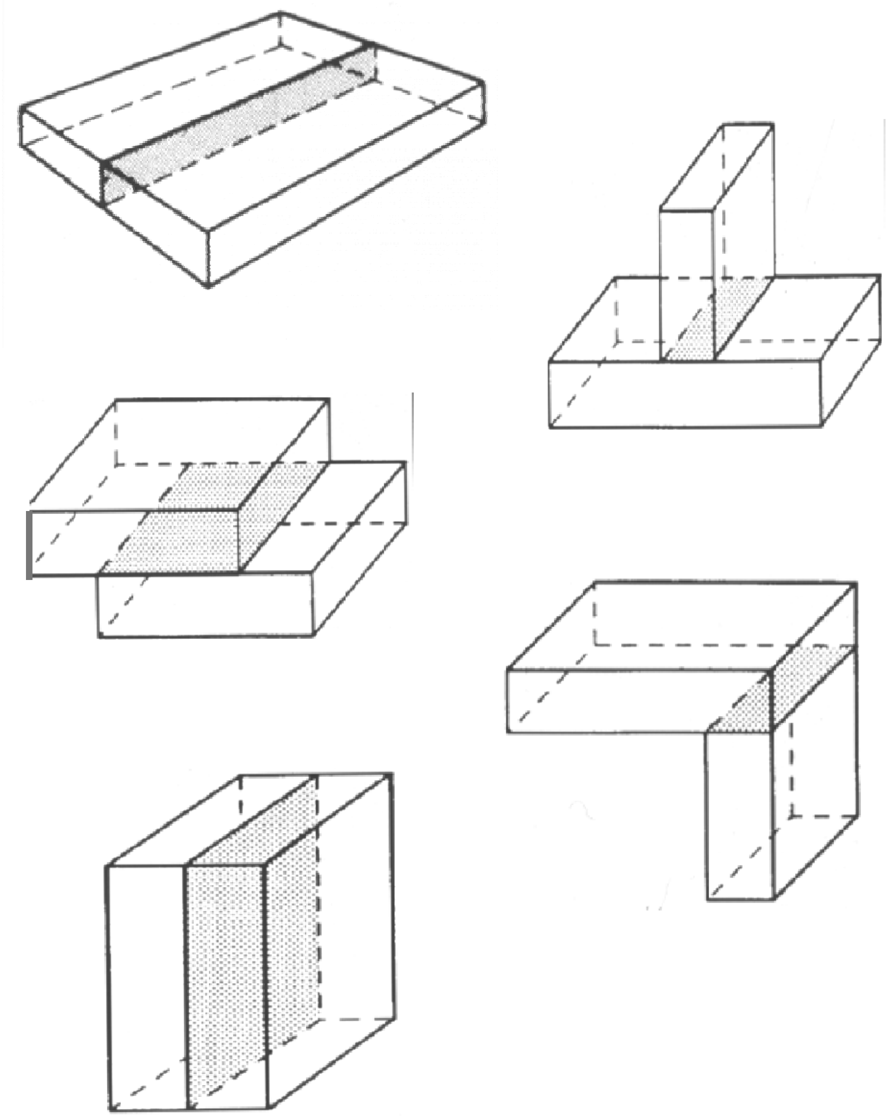
Aspects of Weld Design

- Structural Connection Design Elements
- Types of Joints and Welds (AWS A3.0 - Standard Terms and Definitions)
- Welding/NDE Symbols (AWS A2.4 – Standard Symbols for Welding, Brazing, and Nondestructive Examination)
- Design for Strength
- Design for Fracture Resistance
- Design for Fatigue Resistance
- Effect of Residual Stress and Distortion

Structural Connection Design Elements

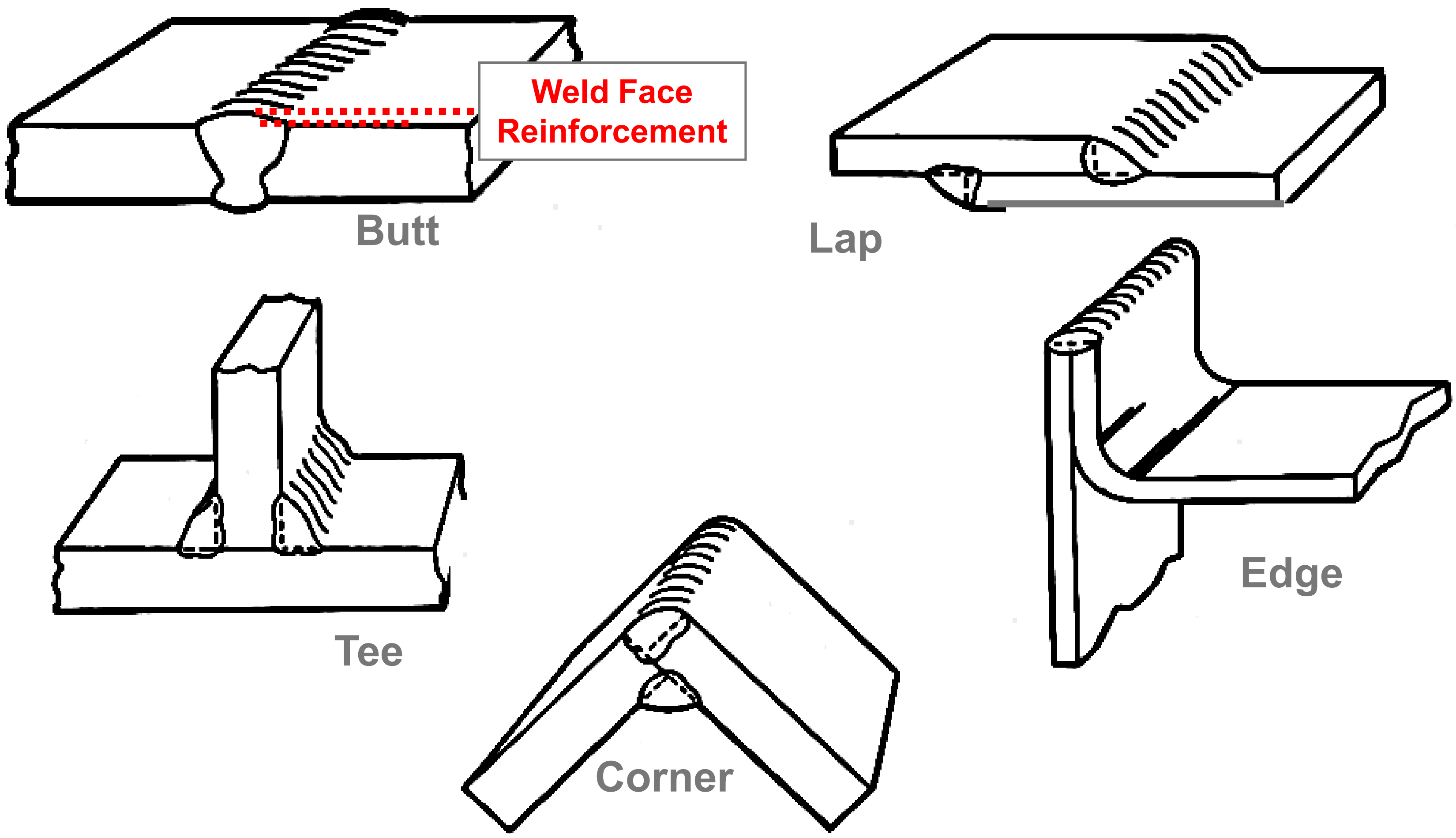
- Connection Types
  - Nontubular (i.e., plate)
  - Tubular
- Basic Joint Types
  - Butt Joint
  - Tee Joint (including skewed-T)
  - Lap Joint
  - Corner Joint
  - Edge Joint
- Basic Weld Types
  - Groove (CJP, PJP)
    - Further classifications see AWS A2.4 and A3.0
  - Fillet
  - Plug and Slot
  - Continuous vs. Intermittent
  - Others for Thin Joints: Spot, Seam
- Welding Positions
  - Flat (1-G or 1-F)
  - Horizontal (2-G or 2-F)
  - Vertical (3-G or 3-F)
  - Overhead (4-G or 4-F)
  - Combination (5-G, 6-G, 6-GR)

Basic Joint Types

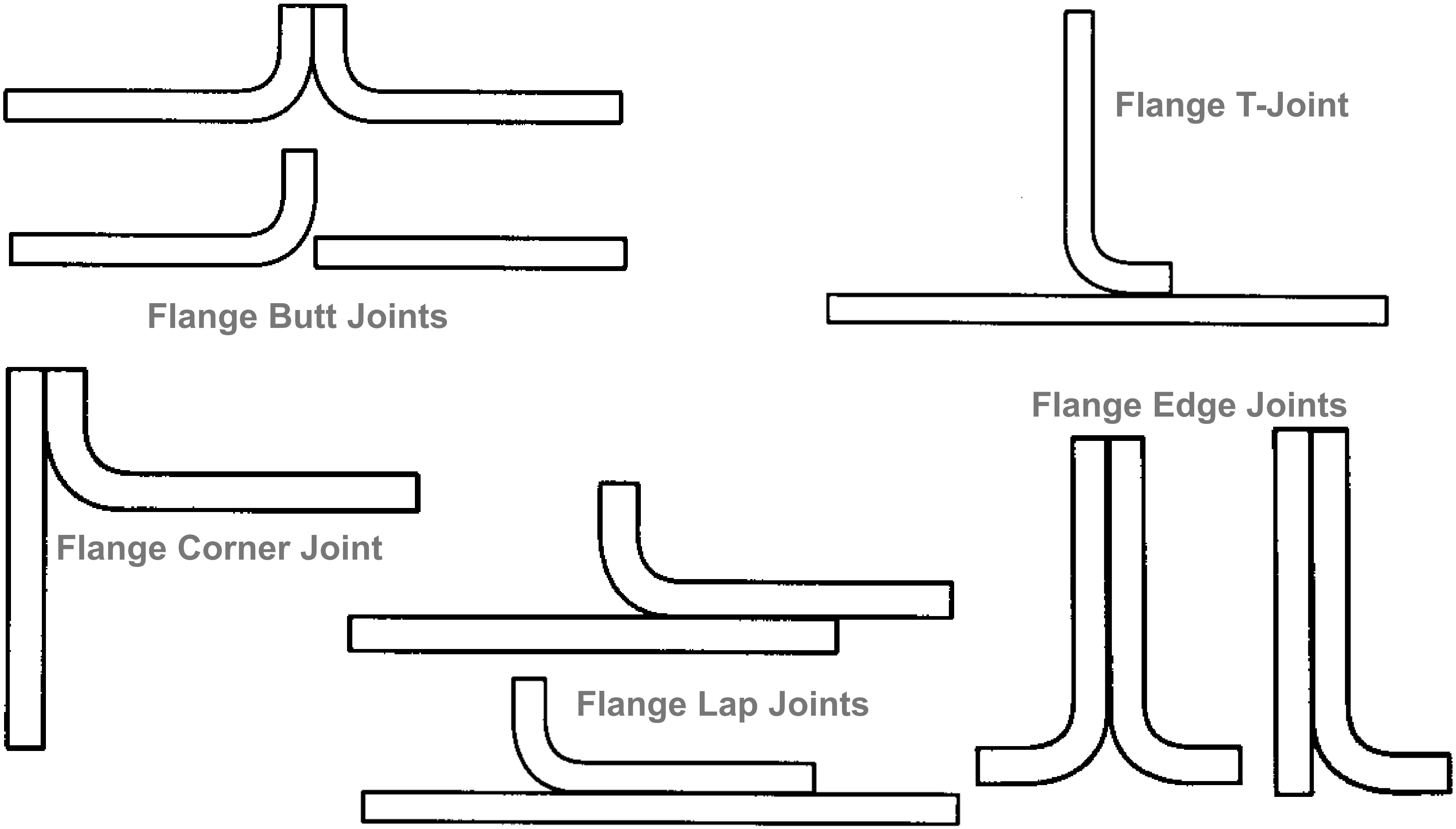


- Butt joint
  - Continuity of section
- Tee joint
  - Flanges or stiffeners
- Lap joint
  - No joint preparation
- Corner joint
- Edge joint
  - Two or more parallel, or nearly parallel members

Joint Type Examples

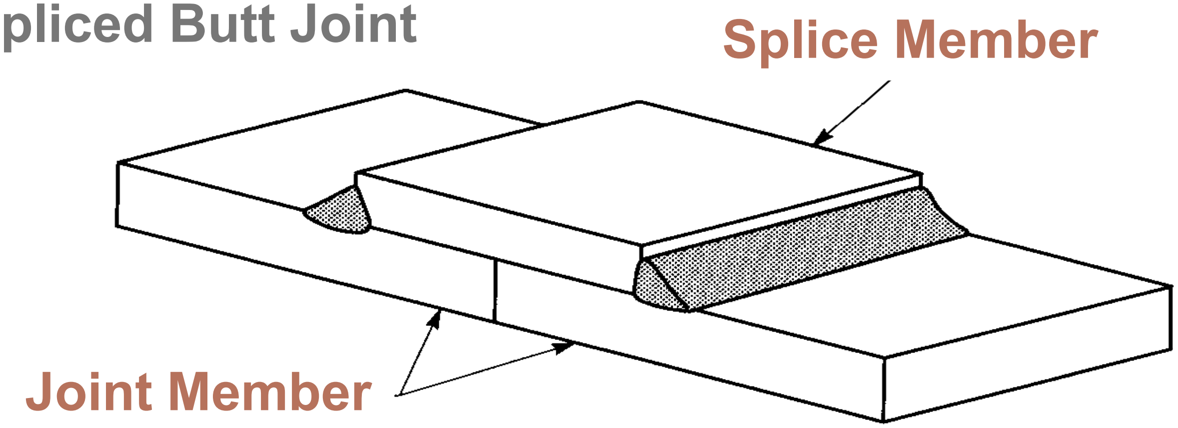


Basic Joint Type Extension – Flanged Joints

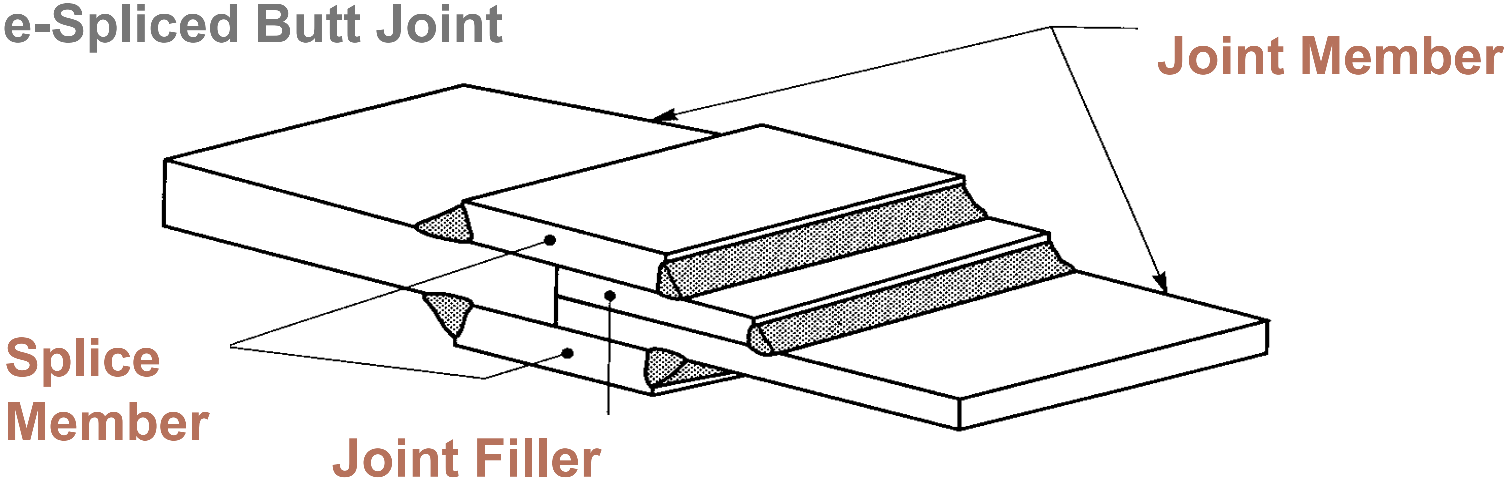


Butt Joint Extension – Spliced Joints

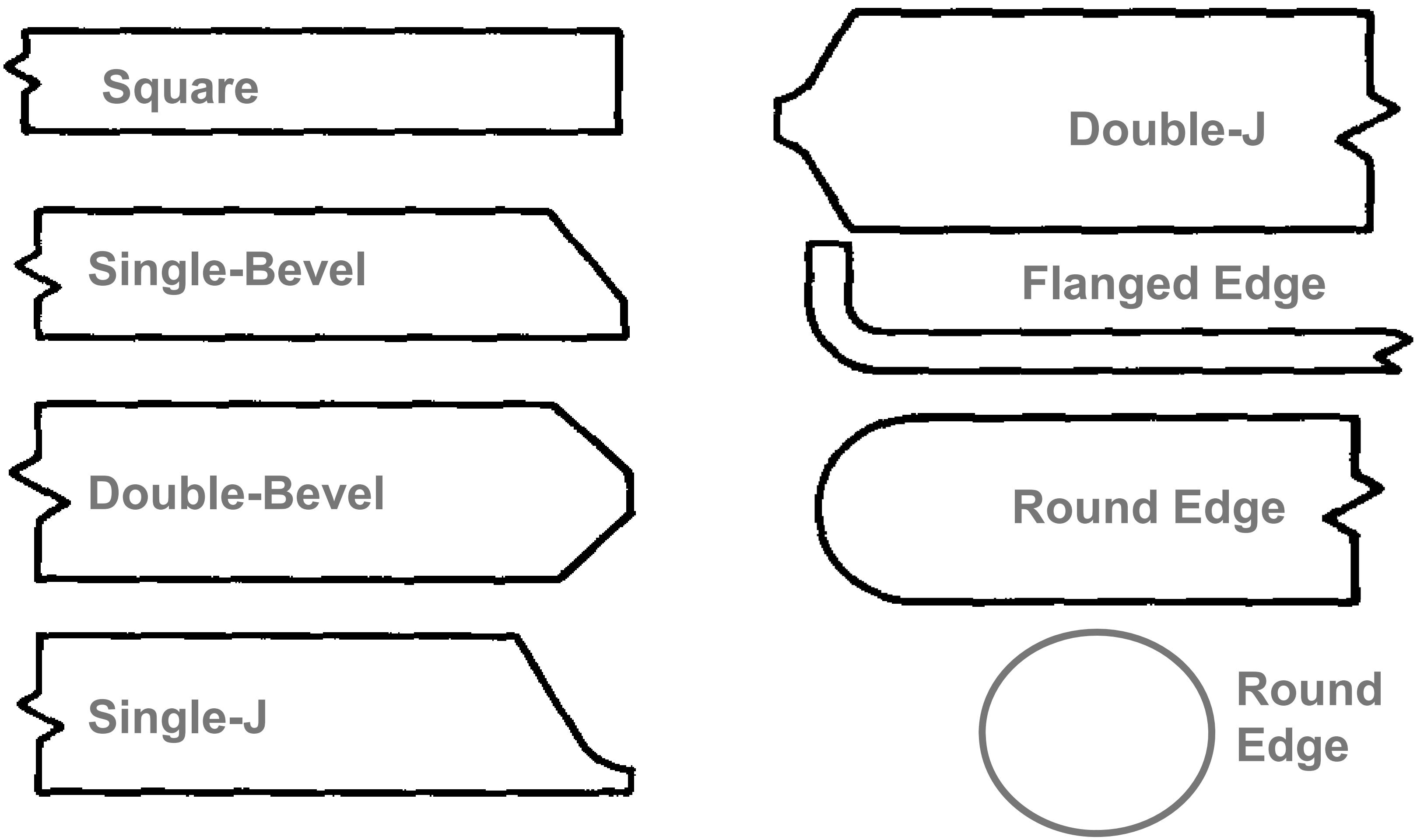
Single-Spliced Butt Joint



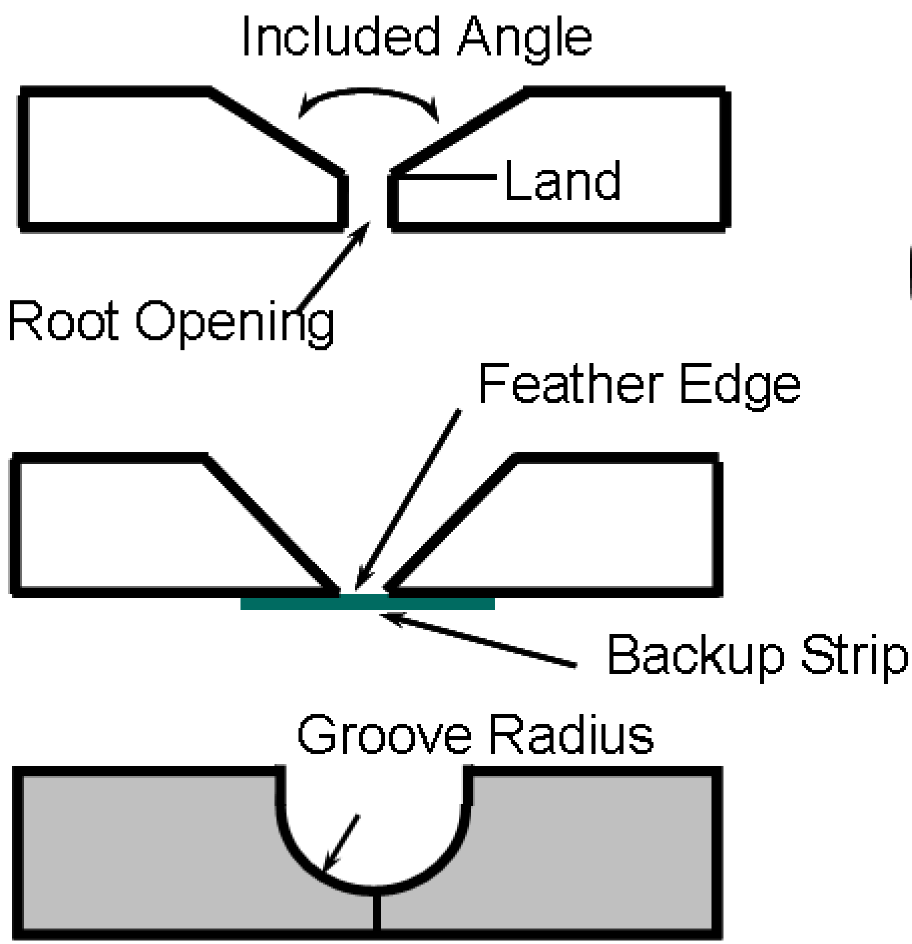
Double-Spliced Butt Joint

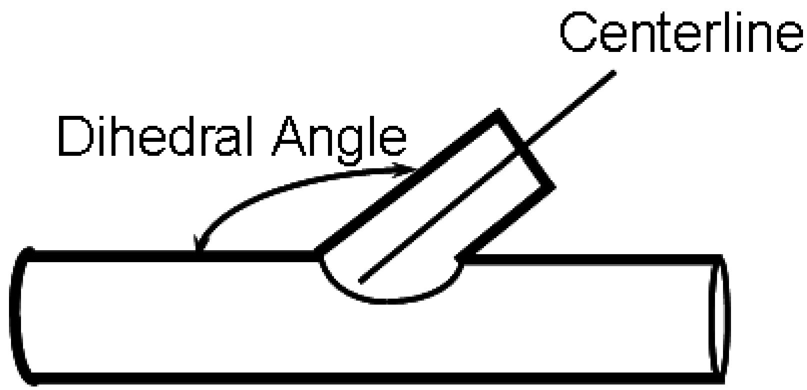


Edge Shapes of Members



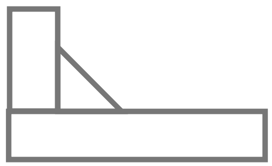
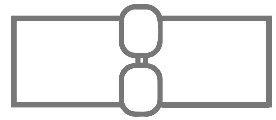
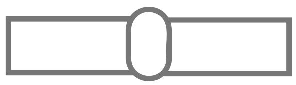
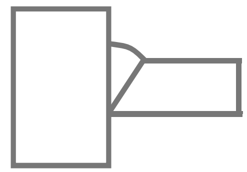
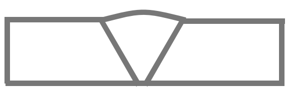
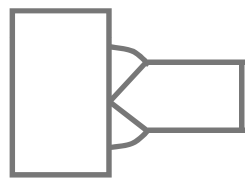
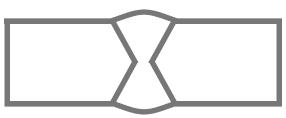
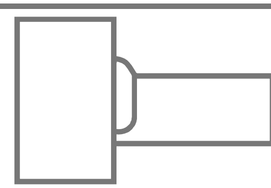
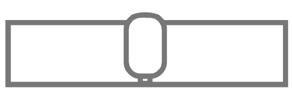
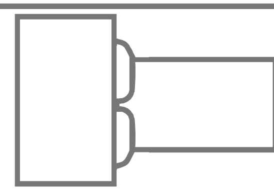
Joint Design Variables



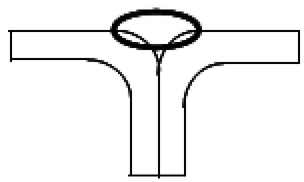
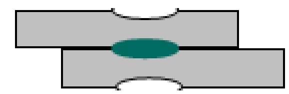
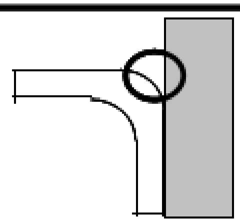
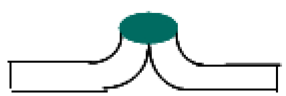
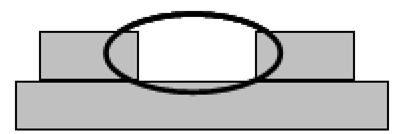
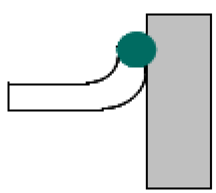
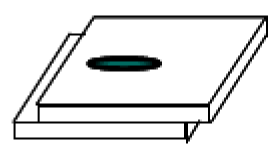


- Root Opening
- Groove Radius
- Included Angle
- Root Face (Land)
- Dihedral Angle

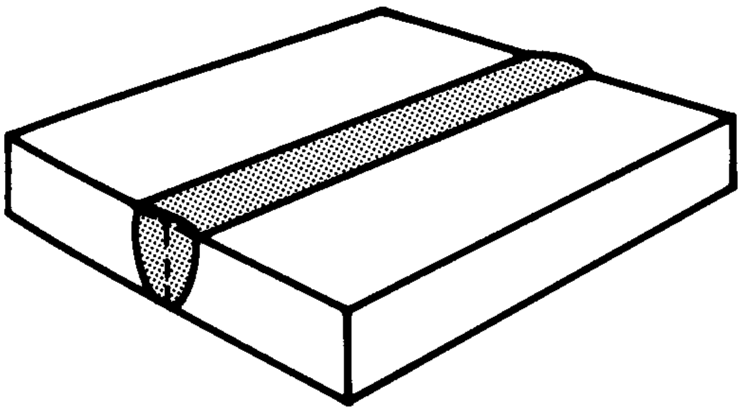
Basic Types of Weld

	Fillet		Double-U Groove
	Square Groove		Single-Bevel Groove
	Single-V Groove		Double-Bevel Groove
	Double-V Groove		Single-J Groove
	Single-U Groove		Double-J Groove

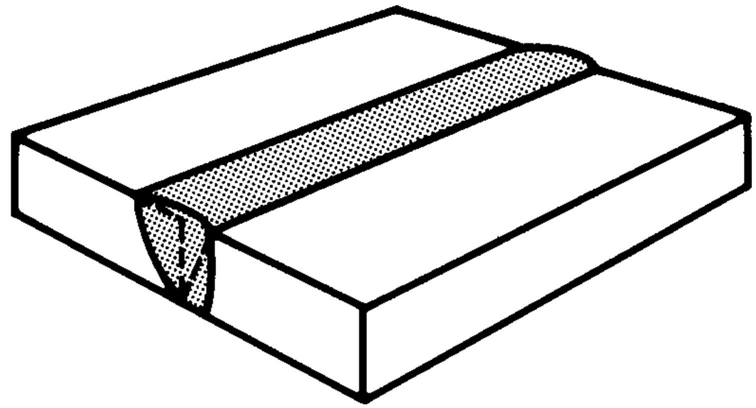
Basic Types of Weld

	Flare-V Groove		Spot or Projection
	Flare-Bevel Groove		Braze
	Edge-Flange		Plug
	Corner-Flange		Slot

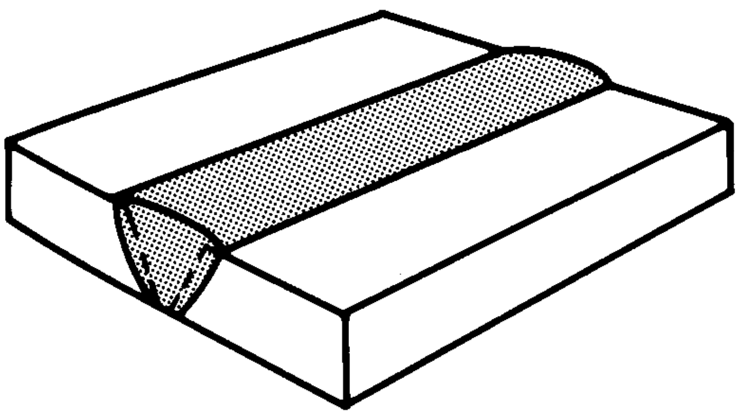
Groove Weld Examples



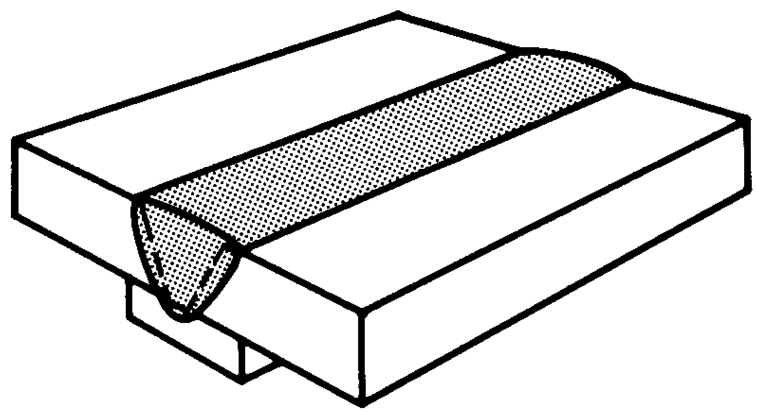
Single-Square-Groove Weld



Single-Bevel-Groove Weld

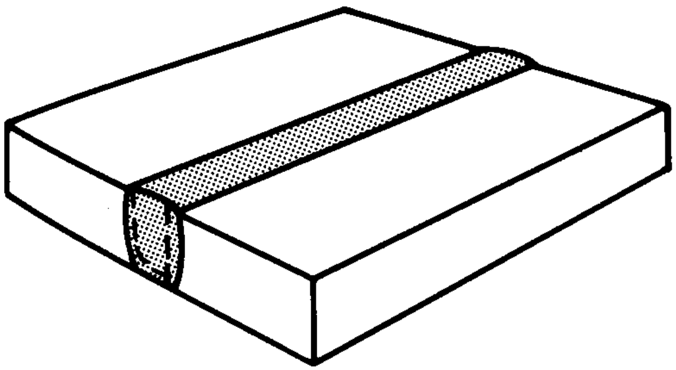


Single-V-Groove Weld

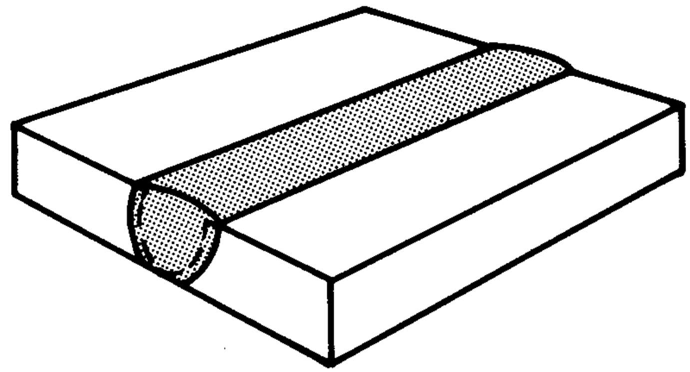


Single-V-Groove Weld
(with Backing)

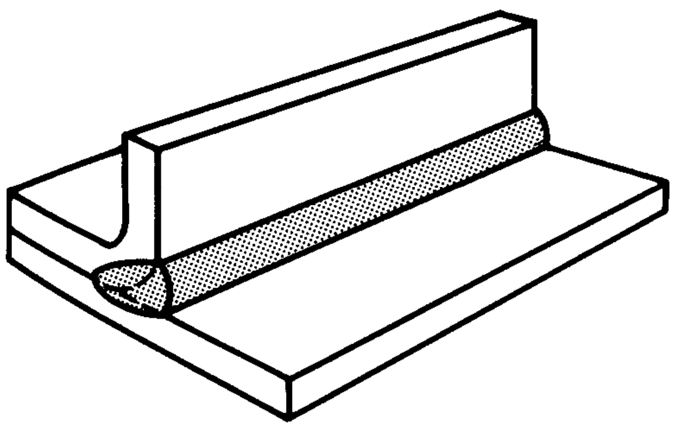
Groove Weld Examples



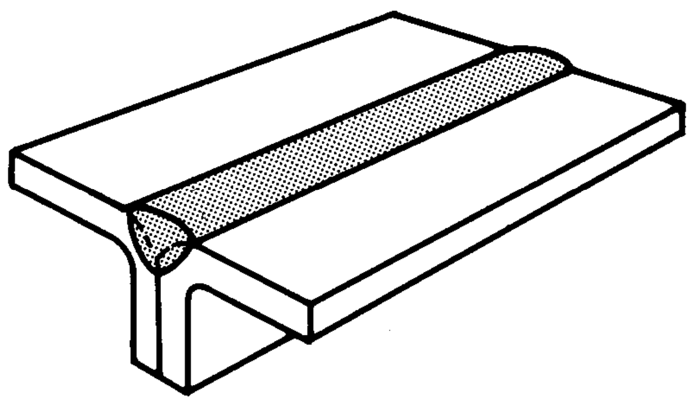
Single-Groove Weld



Single-U-Groove Weld

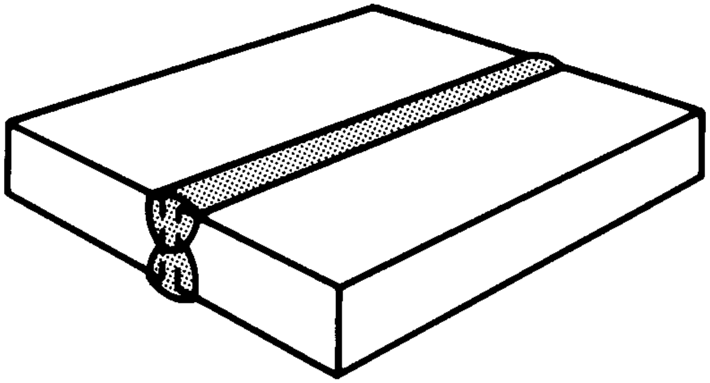


Single-Flare-Bevel-Groove Weld

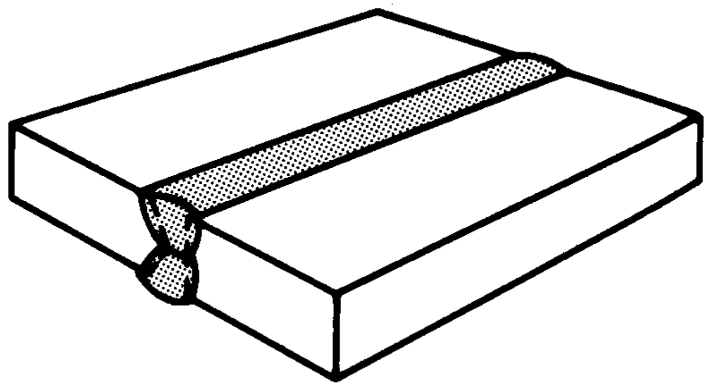


Single-Flare-V-Groove Weld

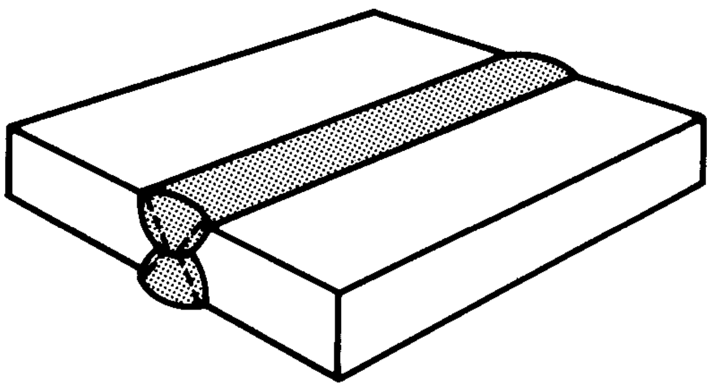
Groove Weld Examples



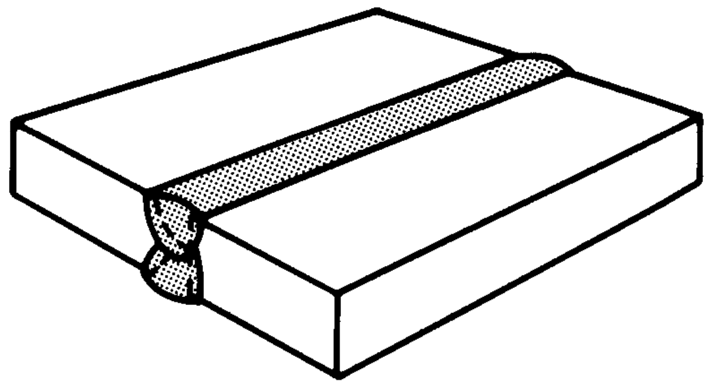
Double-Square-Groove Weld



Double-Bevel-Groove Weld

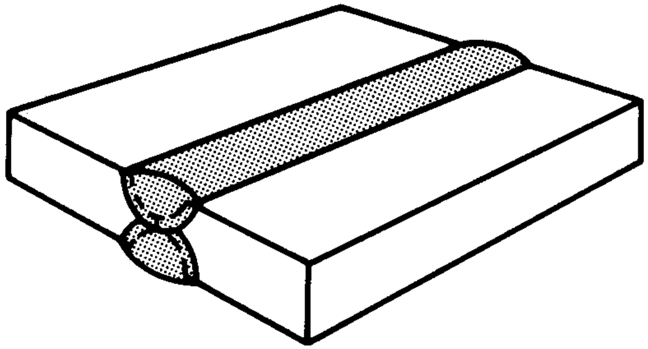


Double-V-Groove Weld

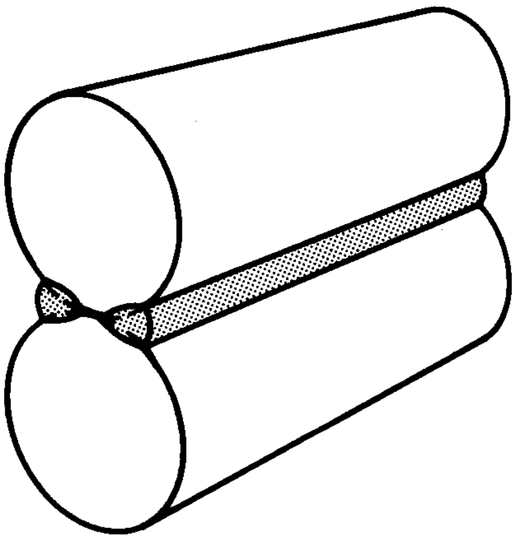


Double-J-Groove Weld

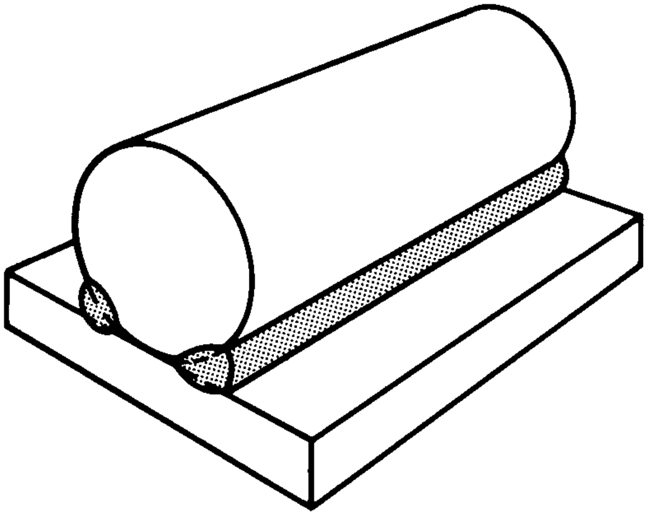
Groove Weld Examples



Double-U-Groove Weld

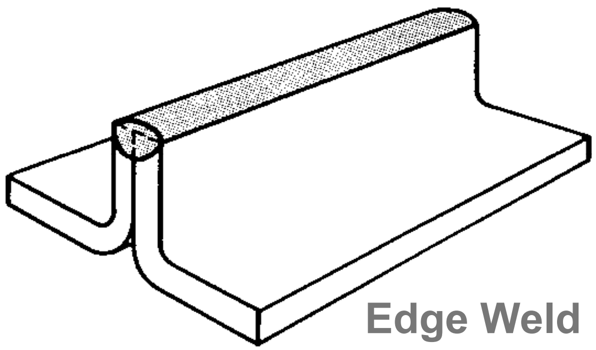


Double-Flare-V-Groove Weld

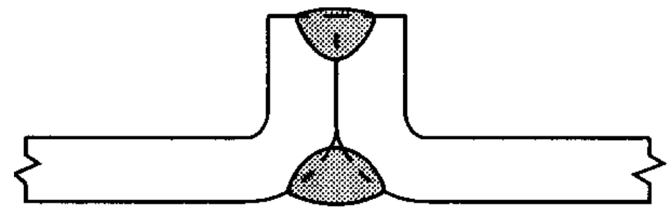


Double-Flare-Bevel-Groove Weld

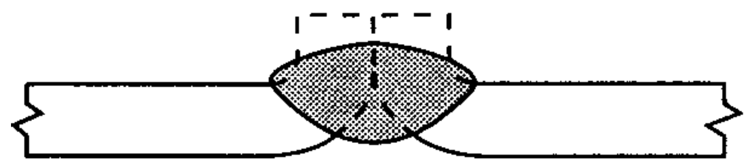
Flare and Edge Welds



Edge Weld in a Flanged Butt Joint

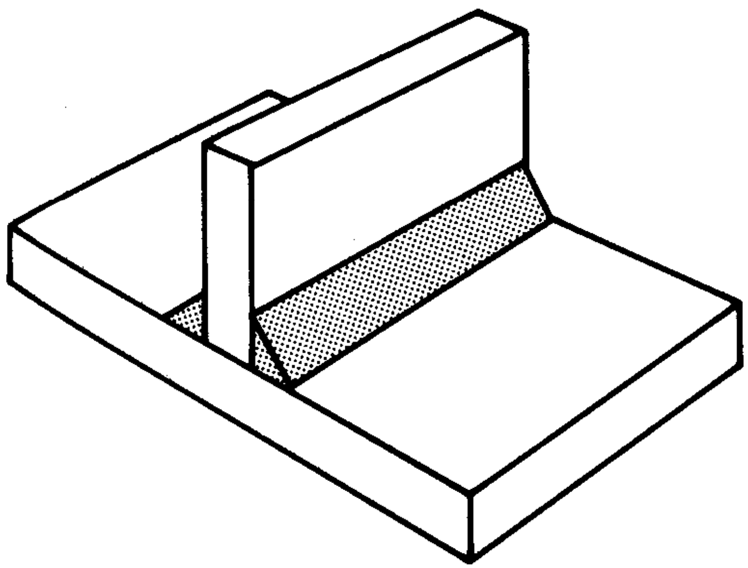


Square-Groove Weld and Flare-V-Groove Weld in a Flanged Butt Joint

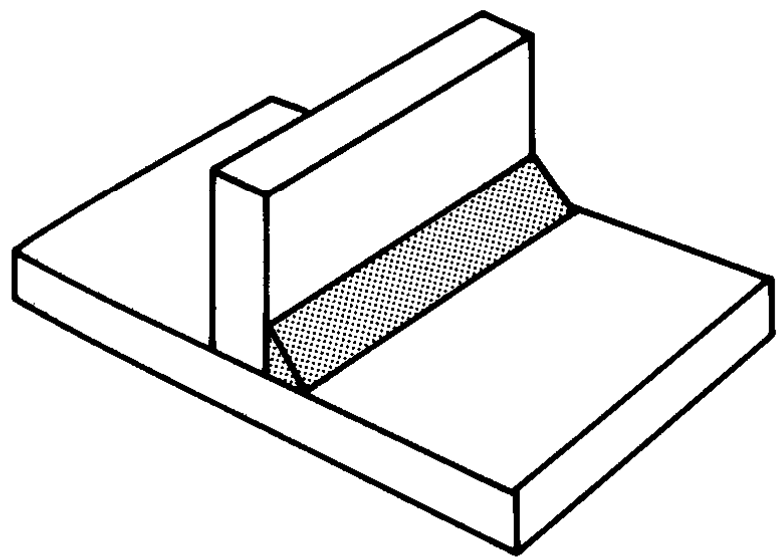


Edge Weld with Melt-through in a Flanged Butt Joint

Fillet Weld Examples

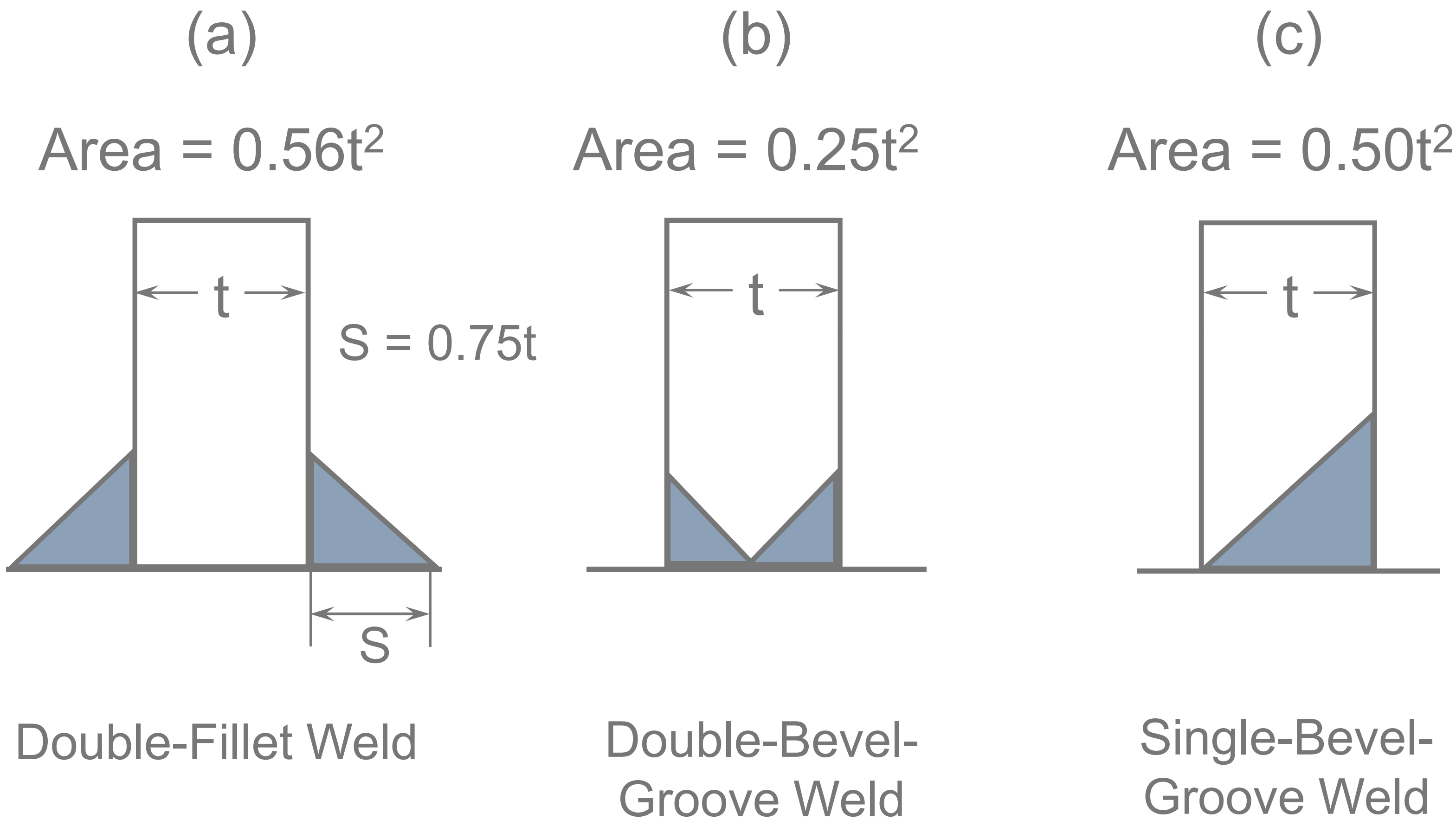


Double Fillet Weld

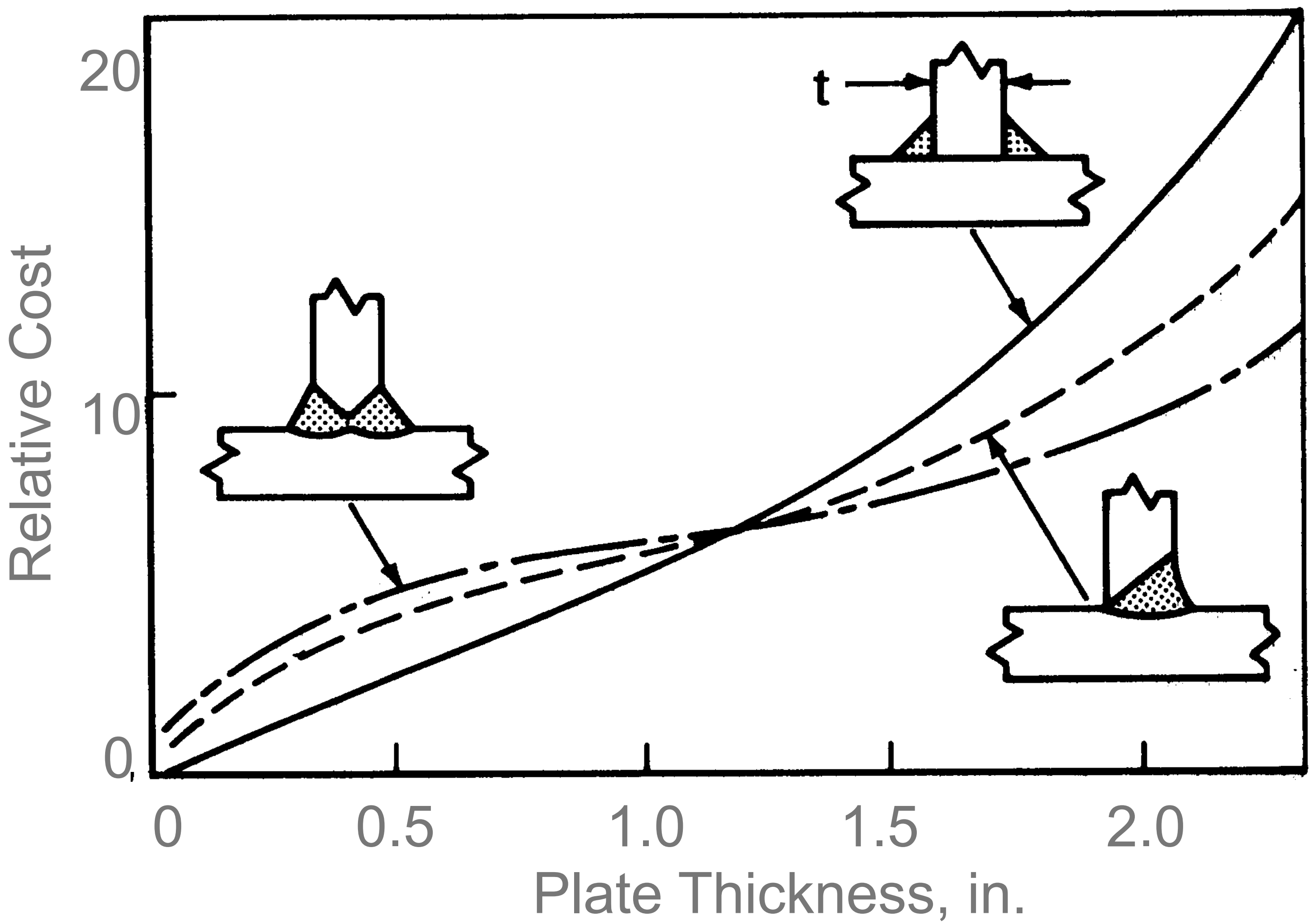


Single Fillet Weld

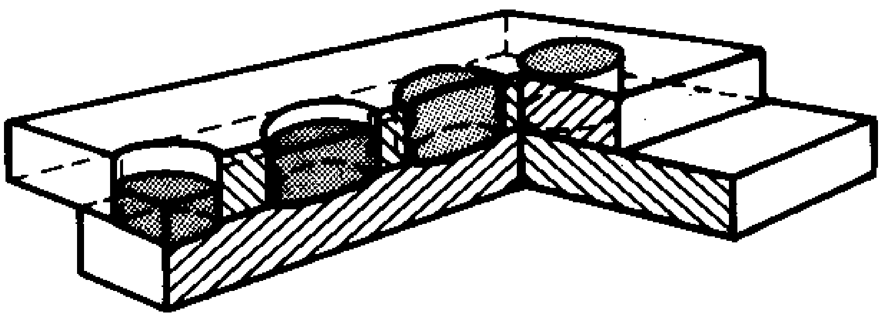
Weld Quantities Comparison



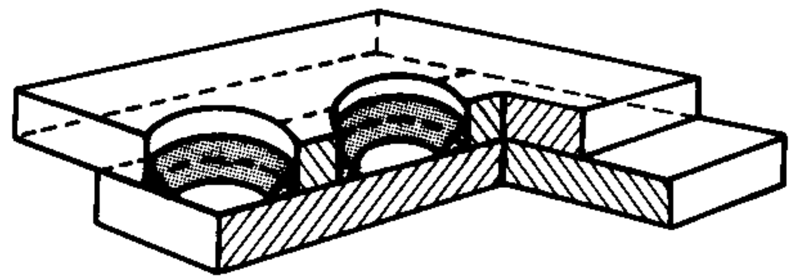
Estimated Relative Costs



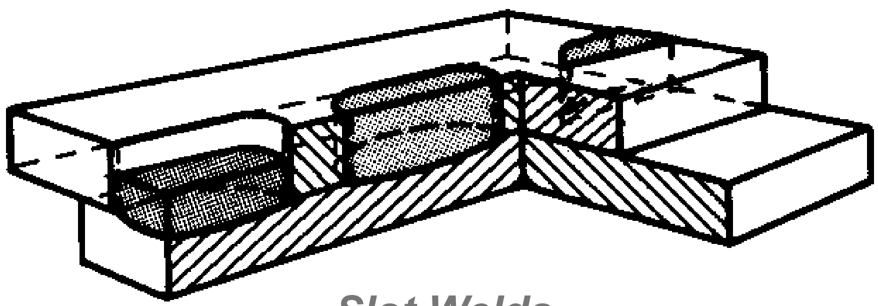
Plug/Slot Weld vs. Fillet Weld in Hole



Plug Welds

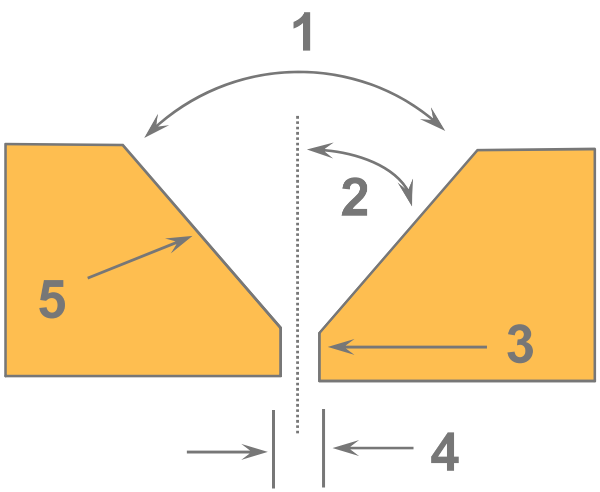


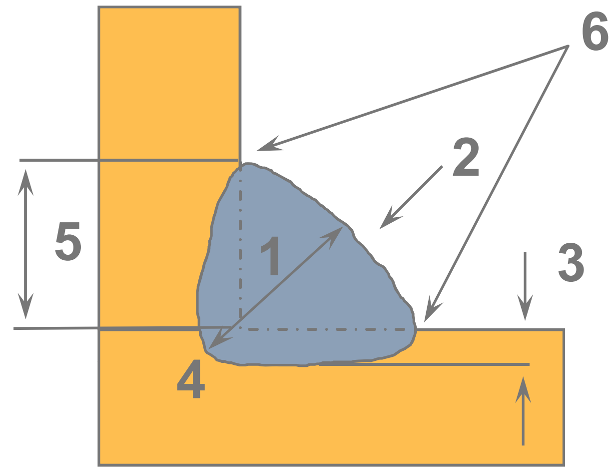
Fillet Welds



Slot Welds

Weld Joint Nomenclature

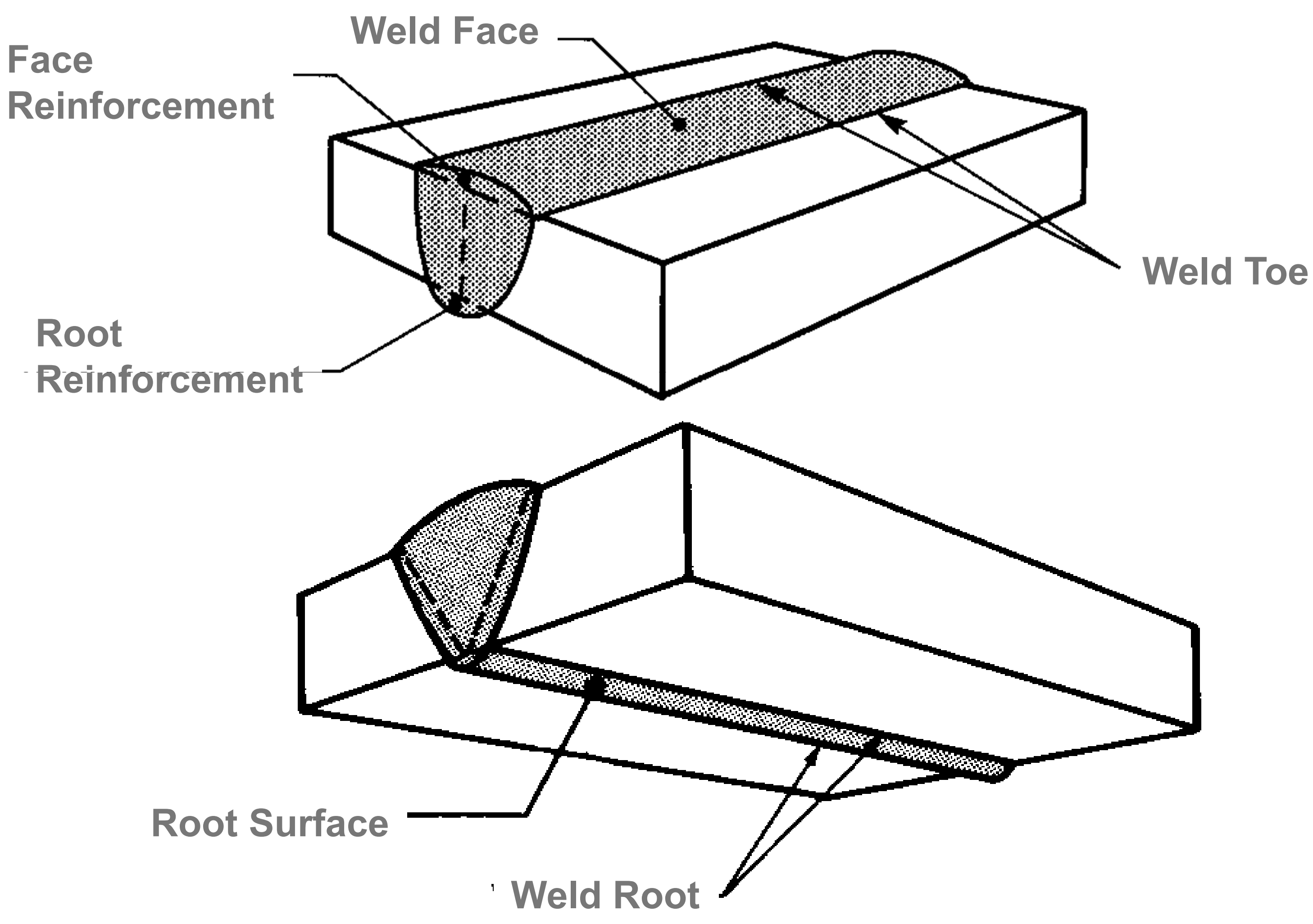




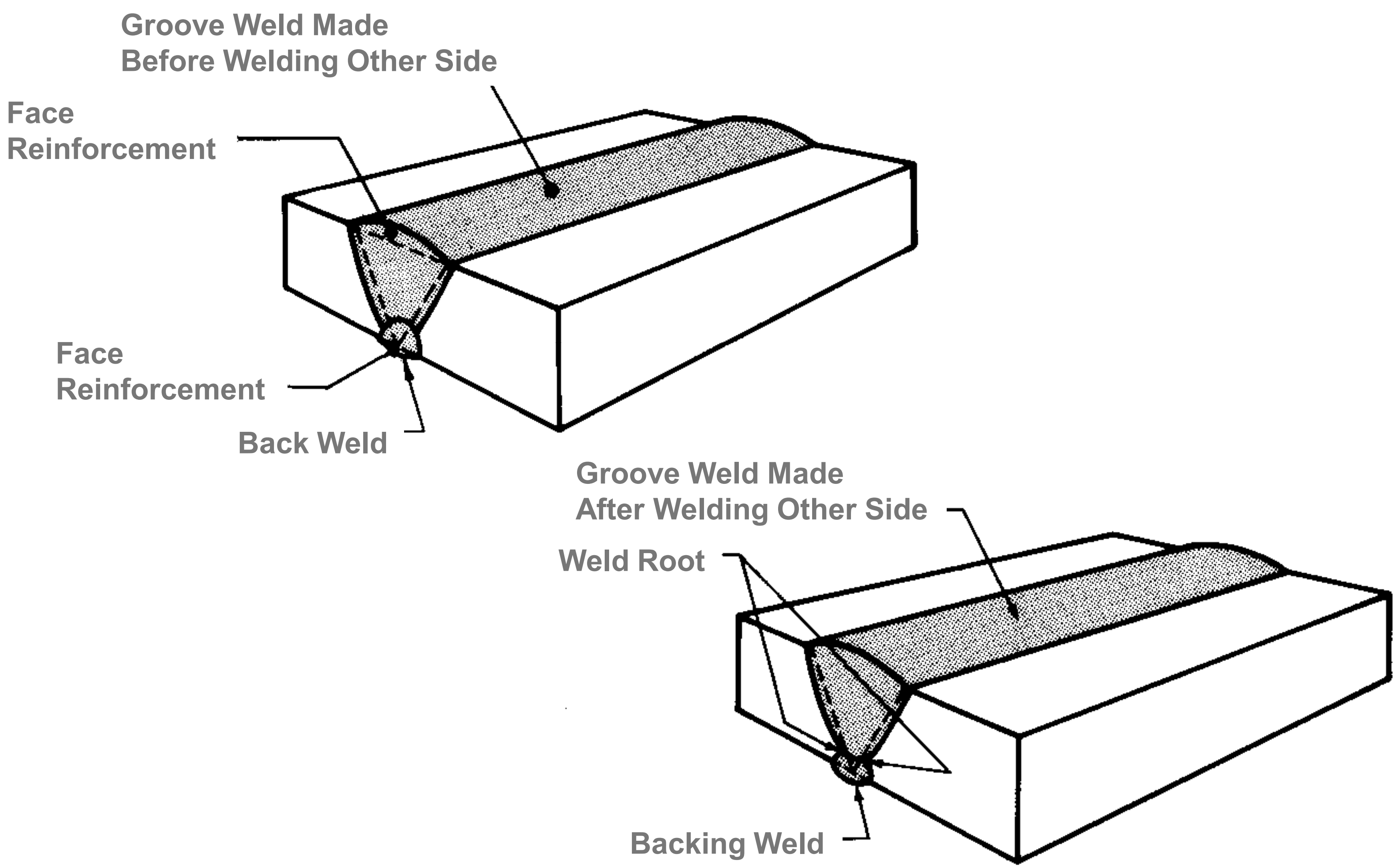
1 - groove angle
2 - bevel angle
3 - root face (land)
4 - root opening (root gap)
5 - groove face

1 - throat
2 - weld face
3 - depth of fusion
4 - root
5 - fillet leg length
6 - weld toe

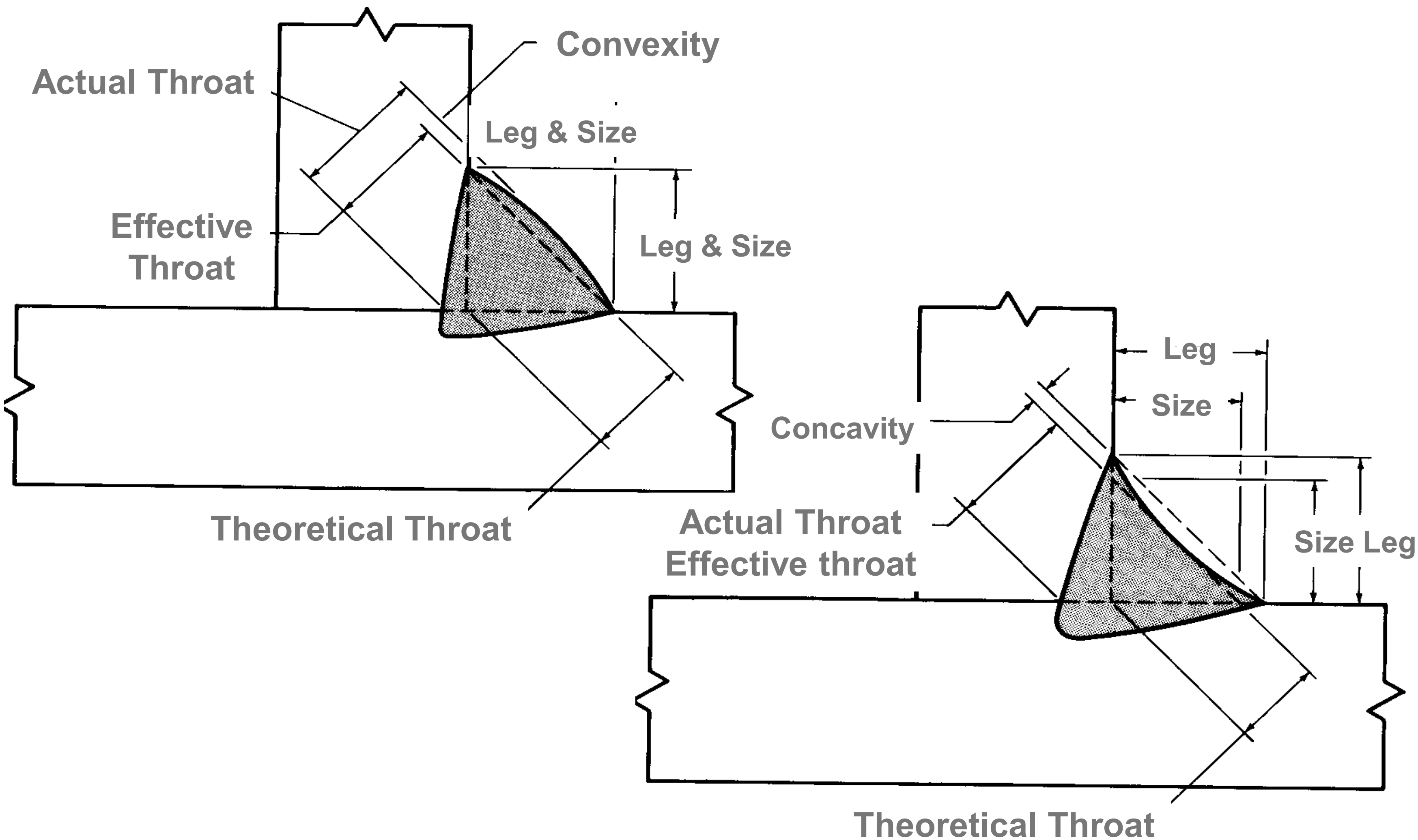
Groove Weld Nomenclature



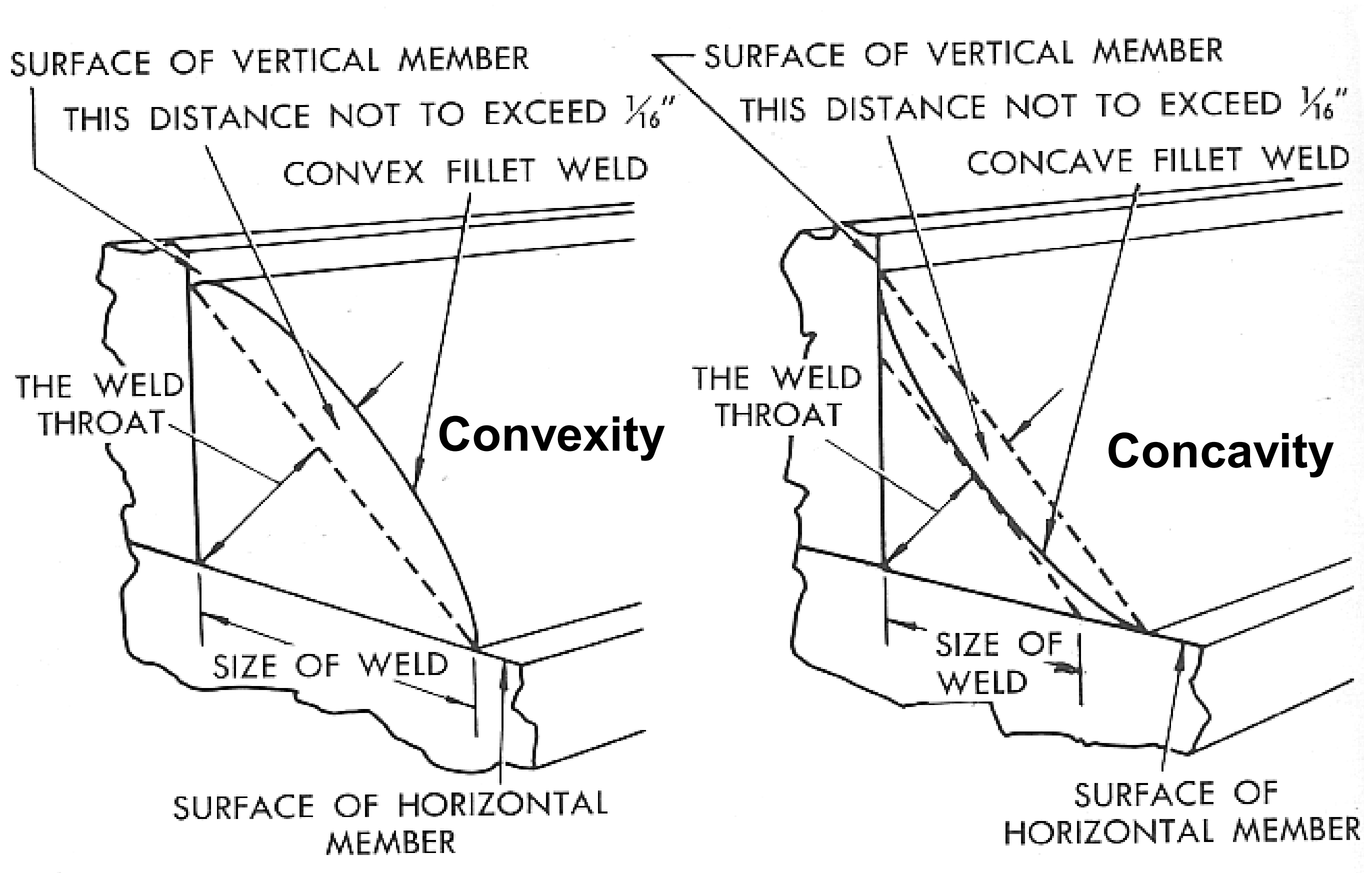
Groove Weld Nomenclature



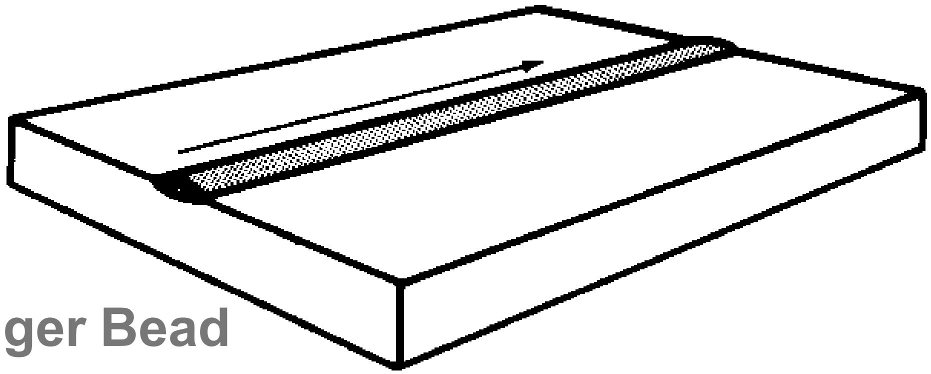
Fillet Weld: Convex and Concave



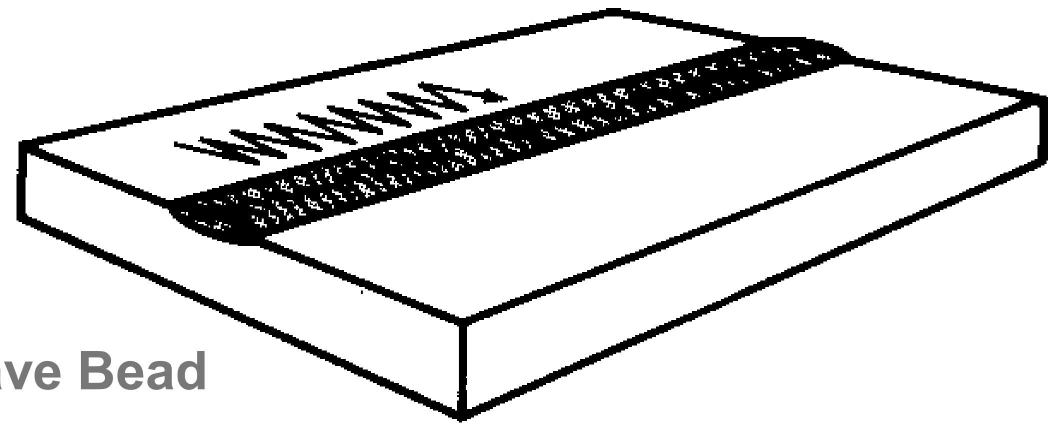
Effective Weld Throat for Design Calculations



Welding Technique

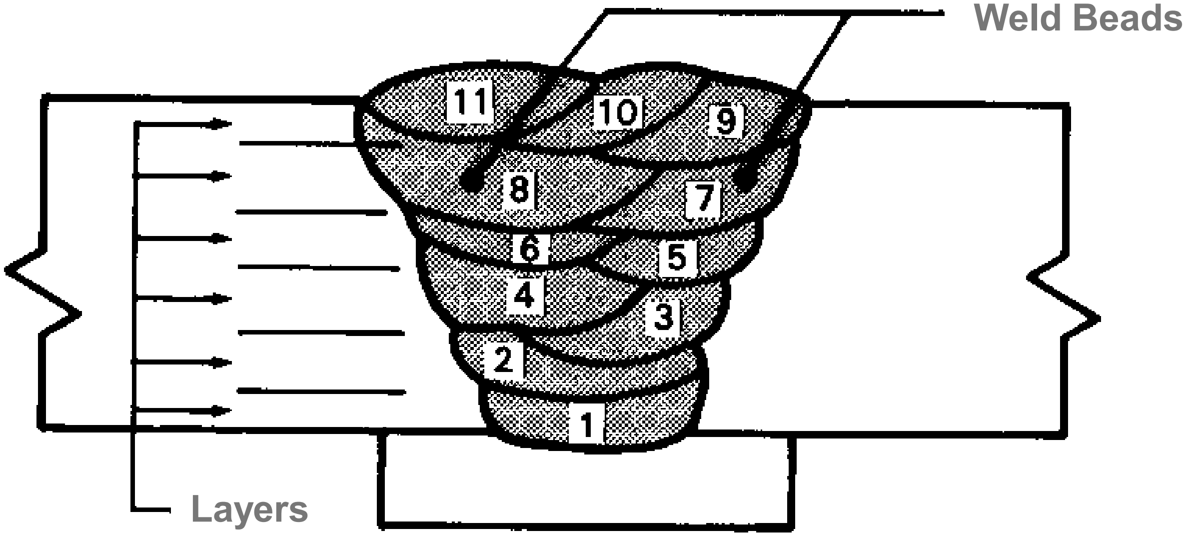


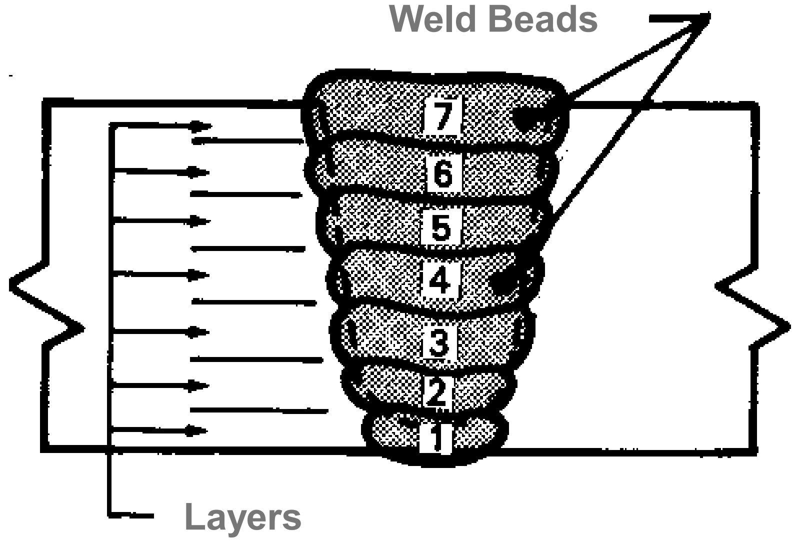
Stringer Bead



Weave Bead

Weld Beads vs. Weld Layers





ASME Section IX – Joint Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-402 Joints	.1	φ Groove Design	X	X	X
	.2	± Backing	X		X
	.4	- Backing			
	.5	+ Backing			
	.6	> Fit-up Gap	X		X
	.10	φ Root Spacing			X
	.11	± Retainers	X		X
	.18	φ Lap Joint Configuration	X		

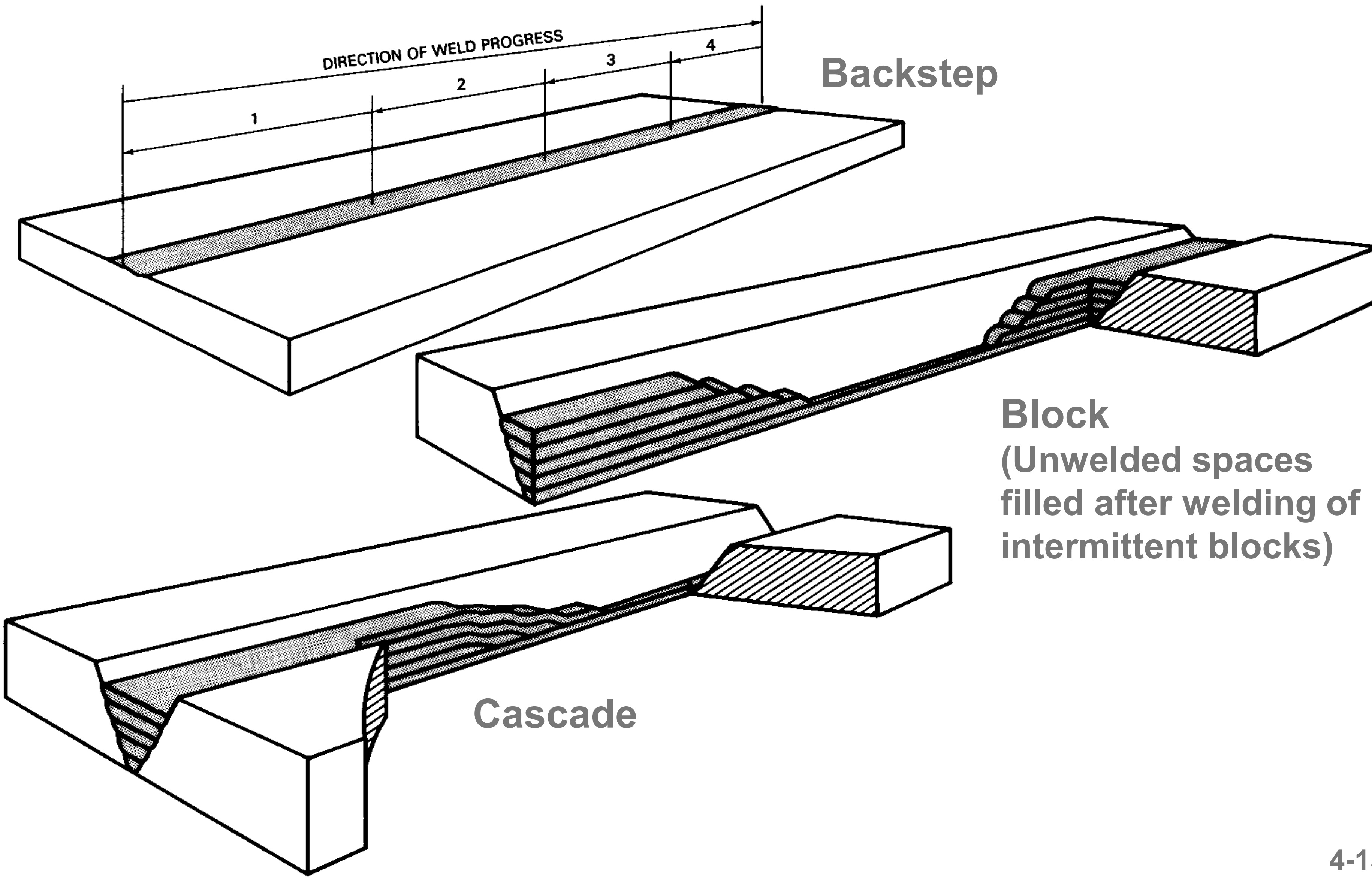
ASME Section IX – Base Material Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-403 Base Materials	.2	Maximum T Qualified	X		
	.3	φ Penetration	X		
	.6	T Limits		X	
	.8	φ T Qualified	X		
	.9	t pass > 1/2-in.	X		
	.10	T Limits (S. Cir. Arc)	X		

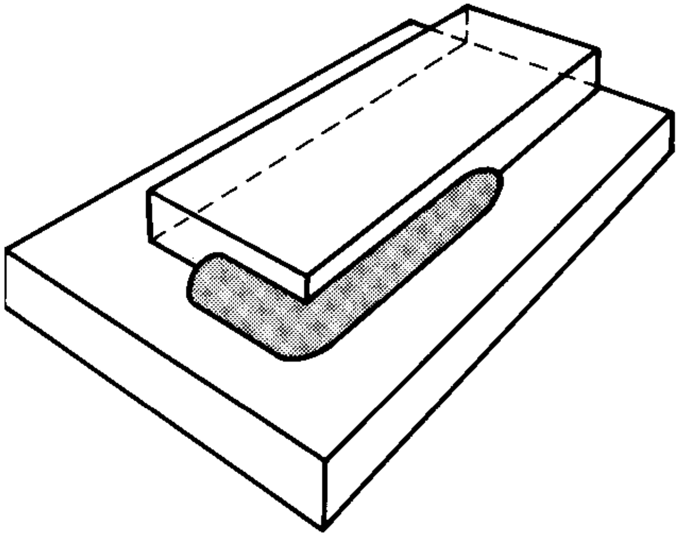
ASME Section IX – Technique Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-410 Technique	.1	φ Stringer/weave			X
	.7	φ Oscillation			X
	.9	φ Multiply to Single Pass/Side		X	X
	.21	1 vs. 2 Sided Welding	X		
	.26	± Peening			X
	.37	φ Single to Multiple Passes			

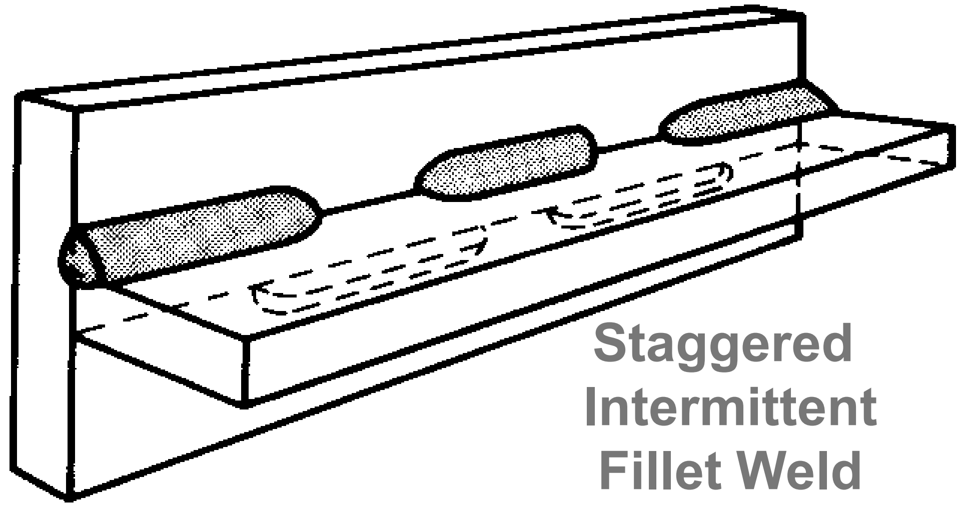
Welding Sequence



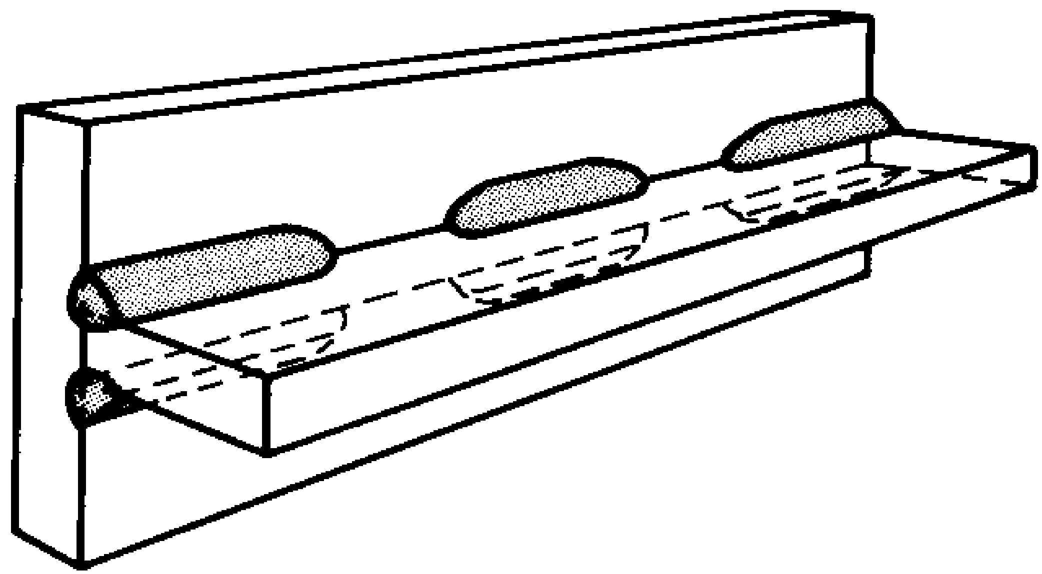
Special Purpose Welds



Boxing
(End Return)

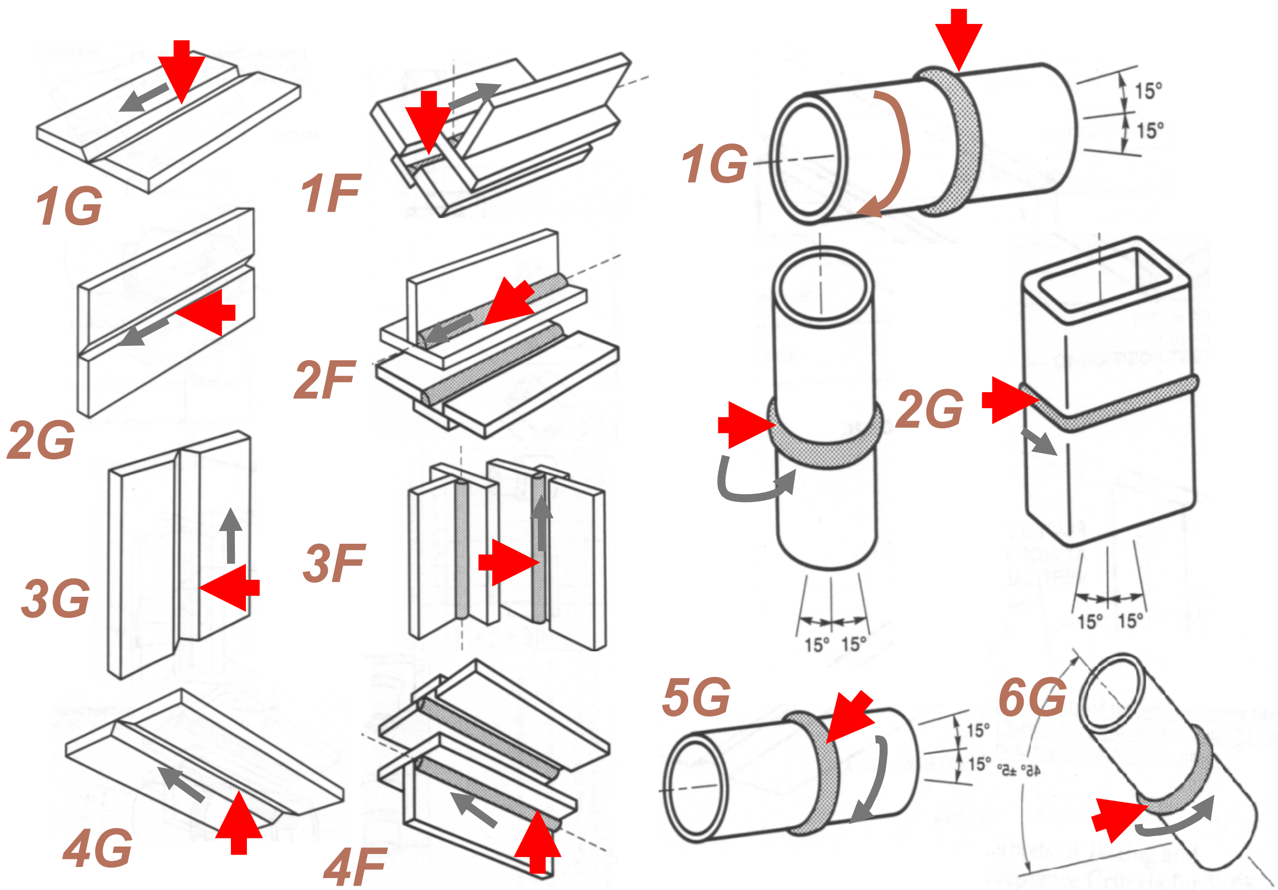


Staggered
Intermittent
Fillet Weld



Chain
Intermittent
Fillet Weld

Welding Position



F - Fillet weld
G - Groove weld

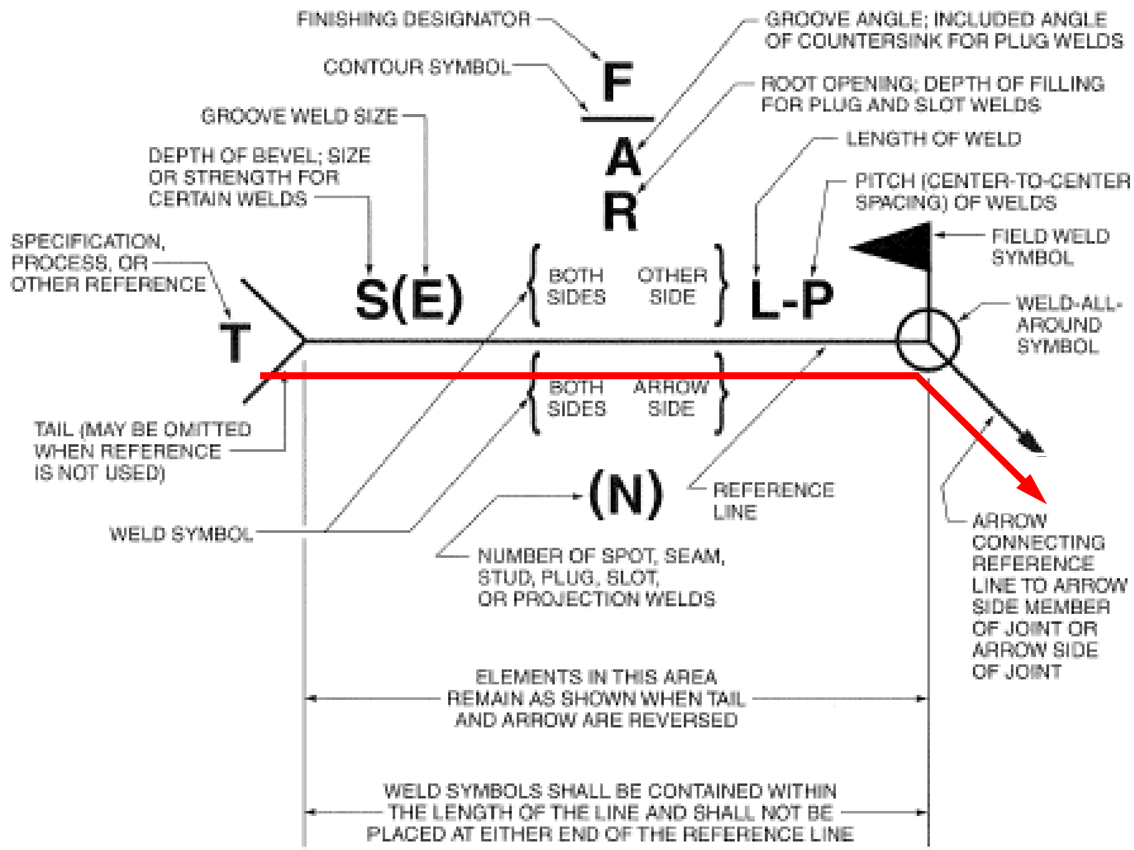
1 - flat
2 - horizontal
3 - vertical
4 - overhead

Welding Symbols

Module 4E

Standard Location of Elements

- Key Elements
  - Arrow
  - Reference Line
  - Tail
  - Weld Symbols
  - Supplementary
  - Symbols
  - Other Details
- Only the REFERENCE LINE and ARROW are required
- Reference line are always horizontal
- Symbol without L-P denotes continuous welds



Symbol Dimensions?

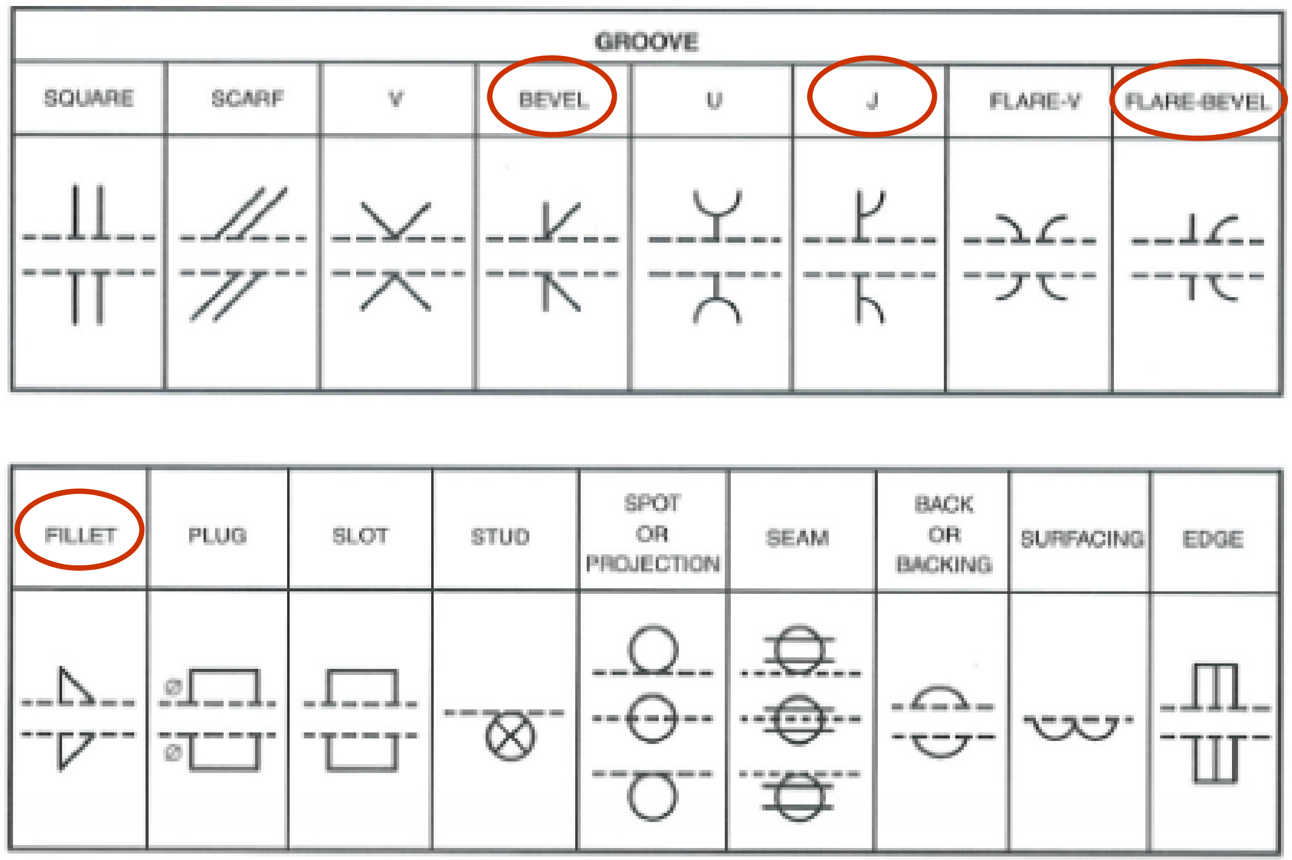
- Tolerances, if required, are to be placed in tail
- Welding Symbols are usually drawn without dimension units such as inches or millimeters
- But, Welding Symbols to be used for publications or those requiring high precision should be dimensioned and have the dimensional tolerances noted within the tail.

Weld Symbols

NOTE:

(1) The reference line is shown dashed for illustrative purposes.

(2) Symbols with a perpendicular leg shall have the perpendicular leg drawn on the left side of the symbol (fillet, bevel-, J-, or flare-bevel-groove)

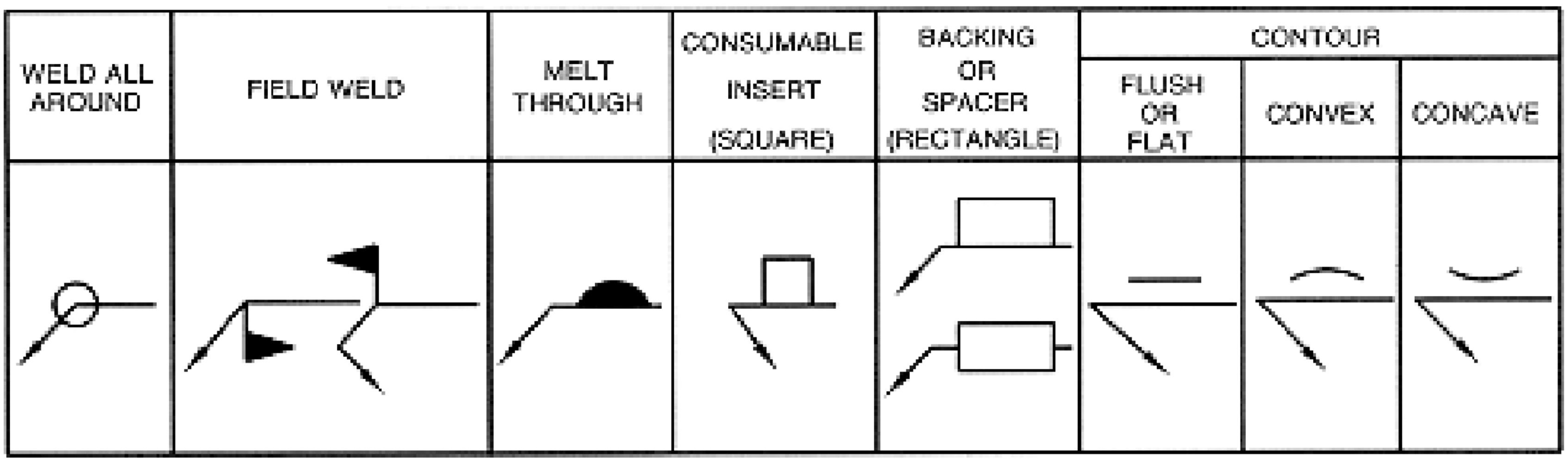


NOTE: The reference line is shown as a dashed line for illustrative purposes.

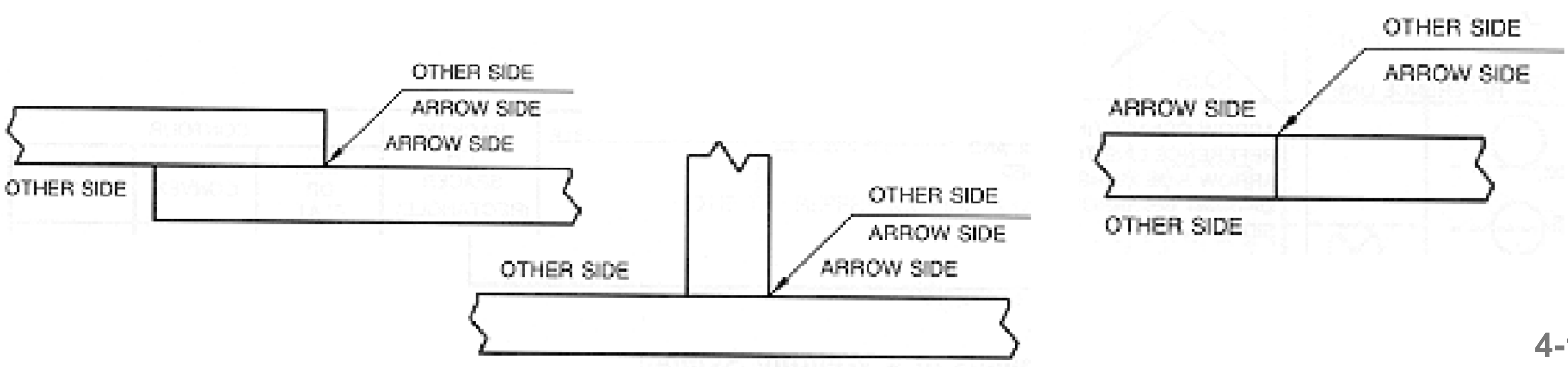
Figure 1—Weld Symbols

Source: AWS A2.4:2007

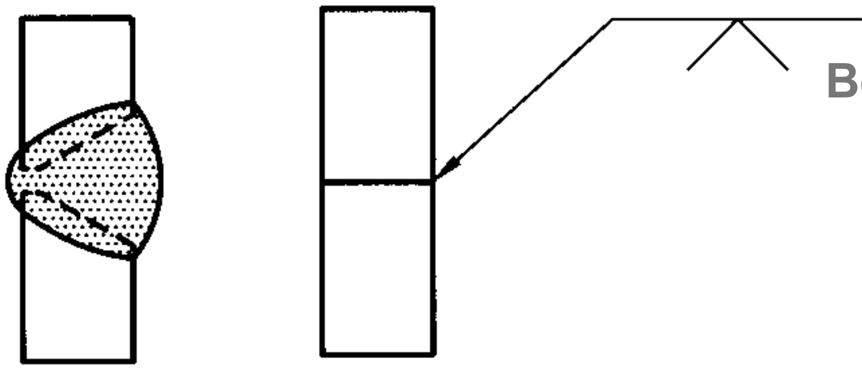
Supplementary Symbols



- Significance of arrow
  - Arrow side below reference line
  - Other side above reference line



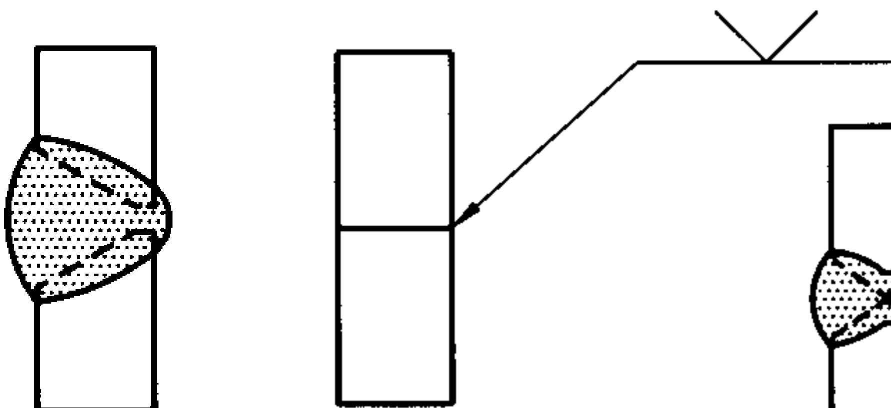
Arrow and Other Side Convention – Examples



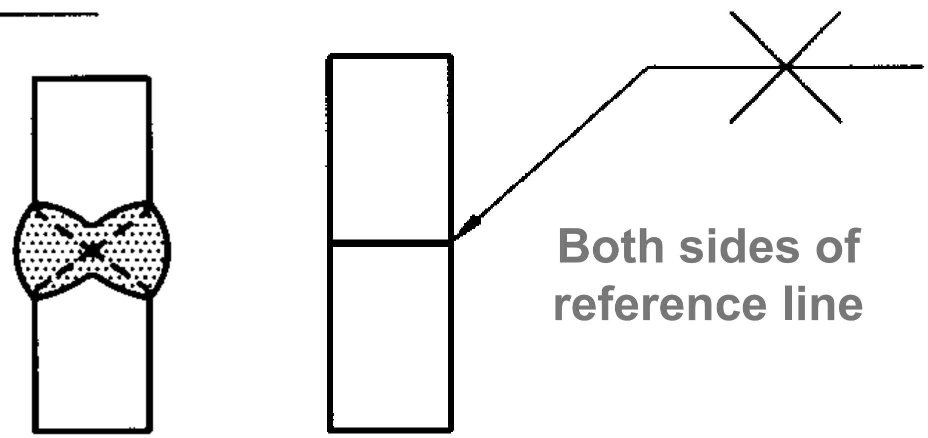
Below reference line

Weld Cross Section Symbol

Above reference line



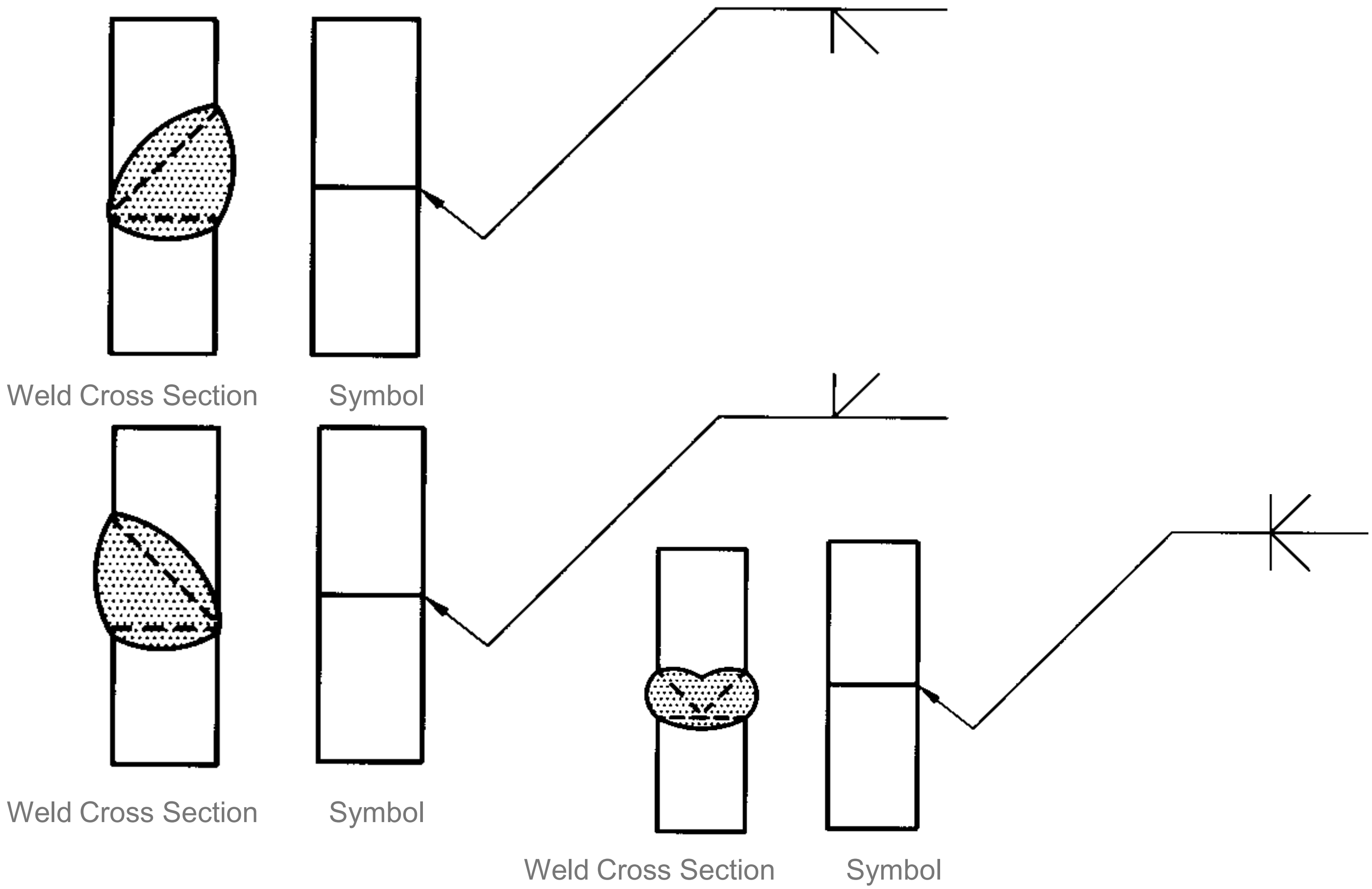
Weld Cross Section Symbol



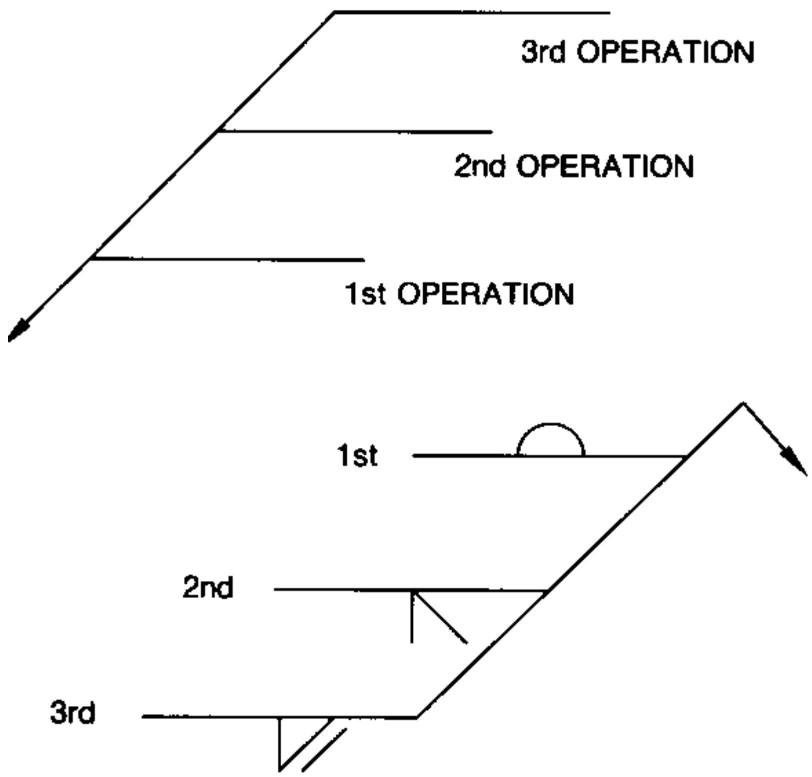
Both sides of reference line

Weld Cross Section Symbol

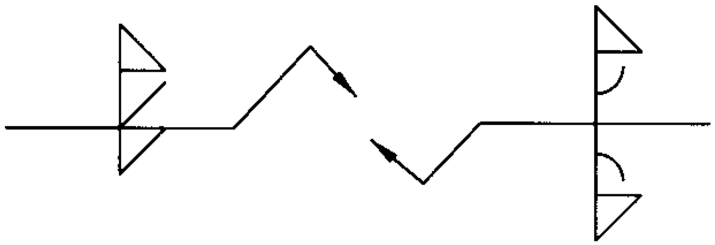
Break in Arrow of Welding Symbol – Examples



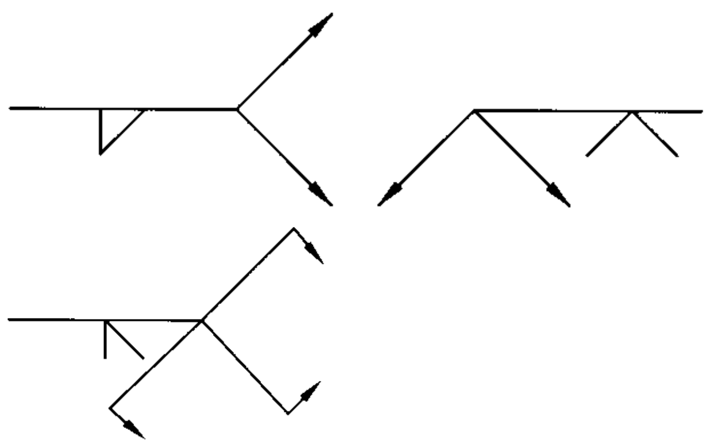
Combined Weld Symbols



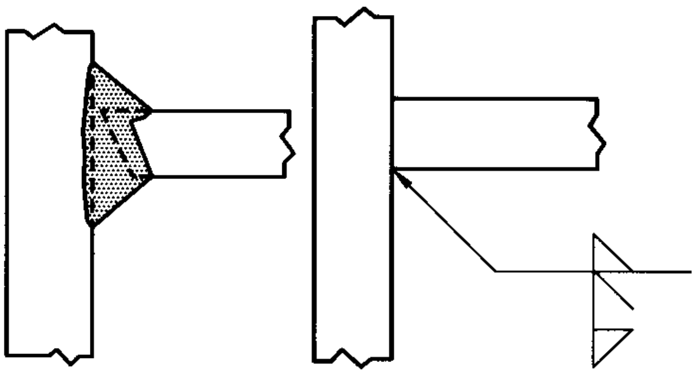
Combined Weld Symbols



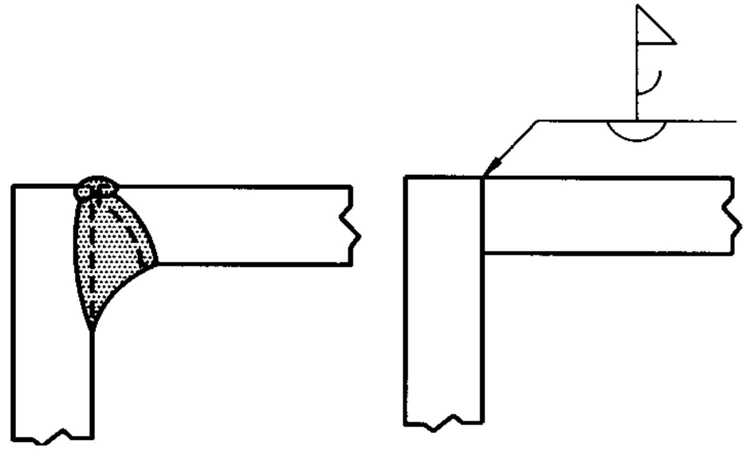
Multiple Arrow Lines



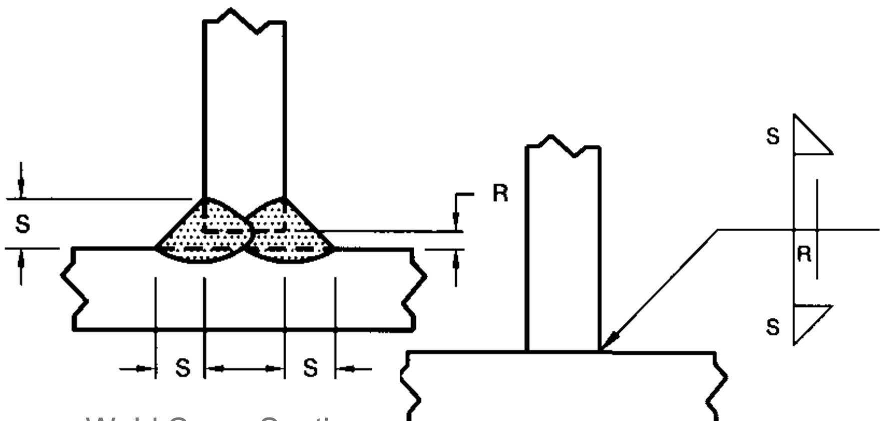
Combined Weld Symbols – Examples



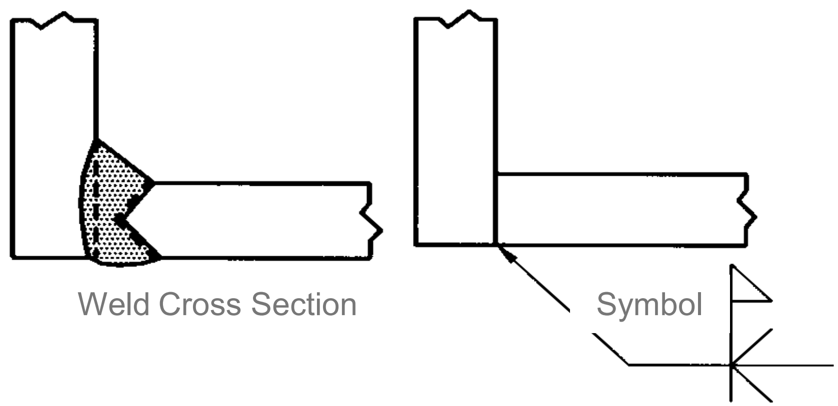
Weld Cross Section   Symbol



Weld Cross Section   Symbol

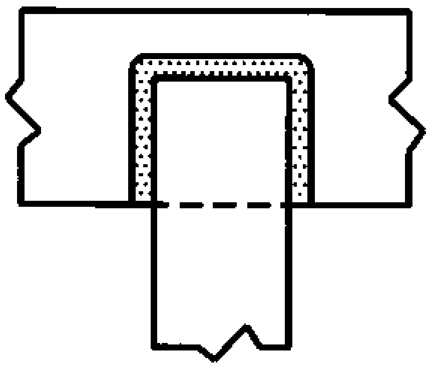


Weld Cross Section

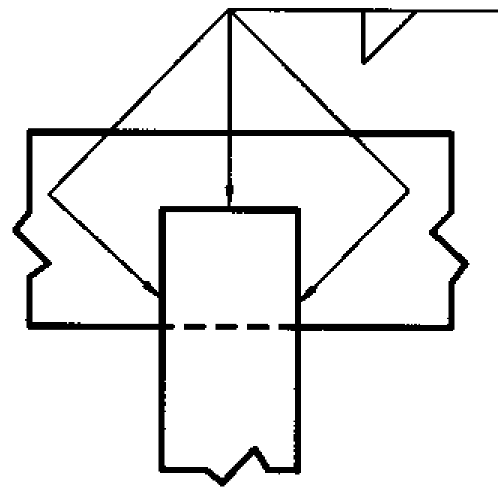


Weld Cross Section   Symbol

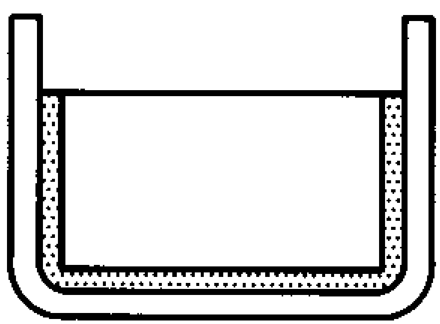
Specification of Extent of Welding Use Multiple Arrows



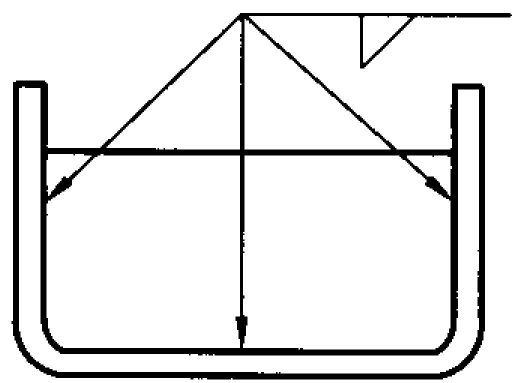
Welds



Symbols



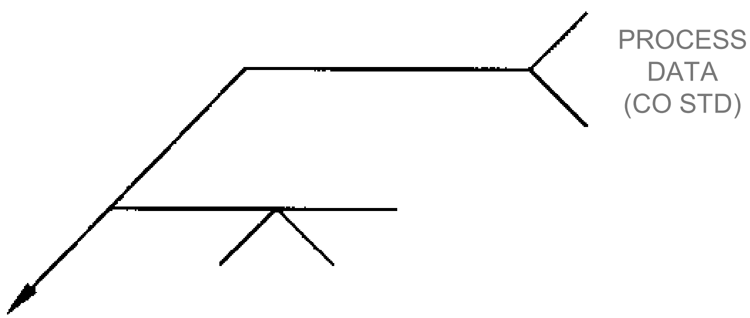
Welds



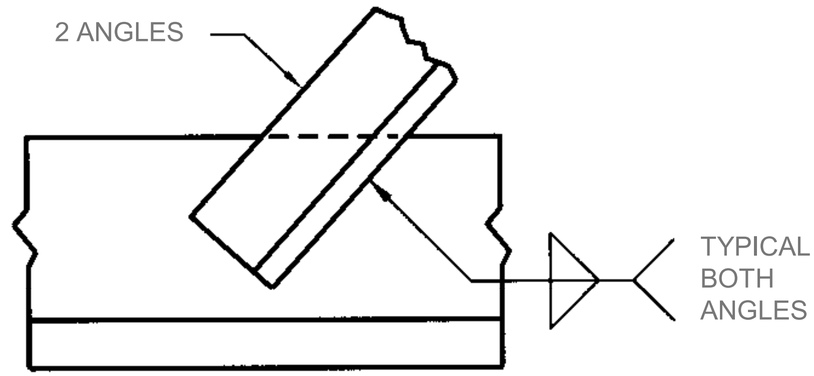
Symbols

Supplementary Information

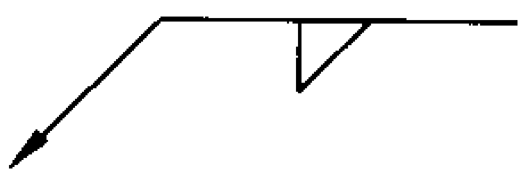
Supplementary Data



Hidden Members of the Same as a Visible Member

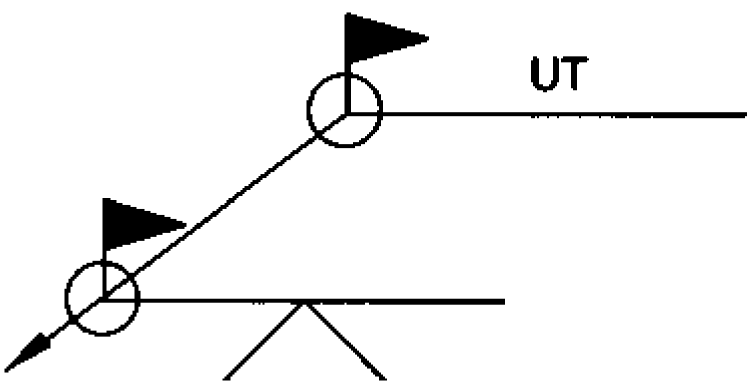


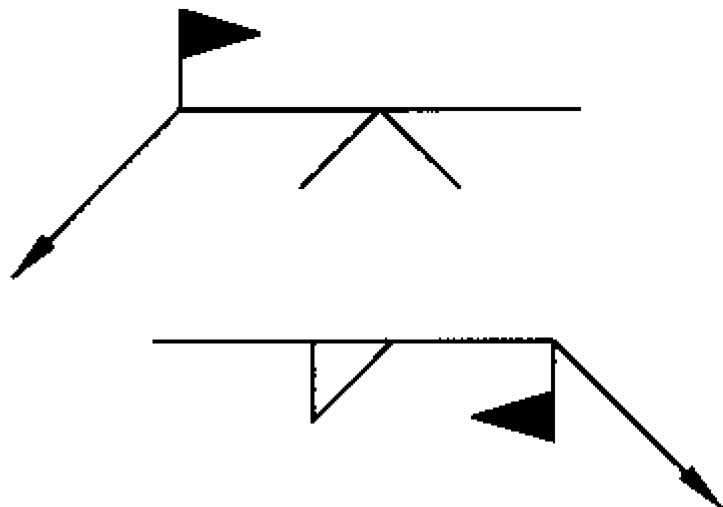
Omission of Tail When No References are Required



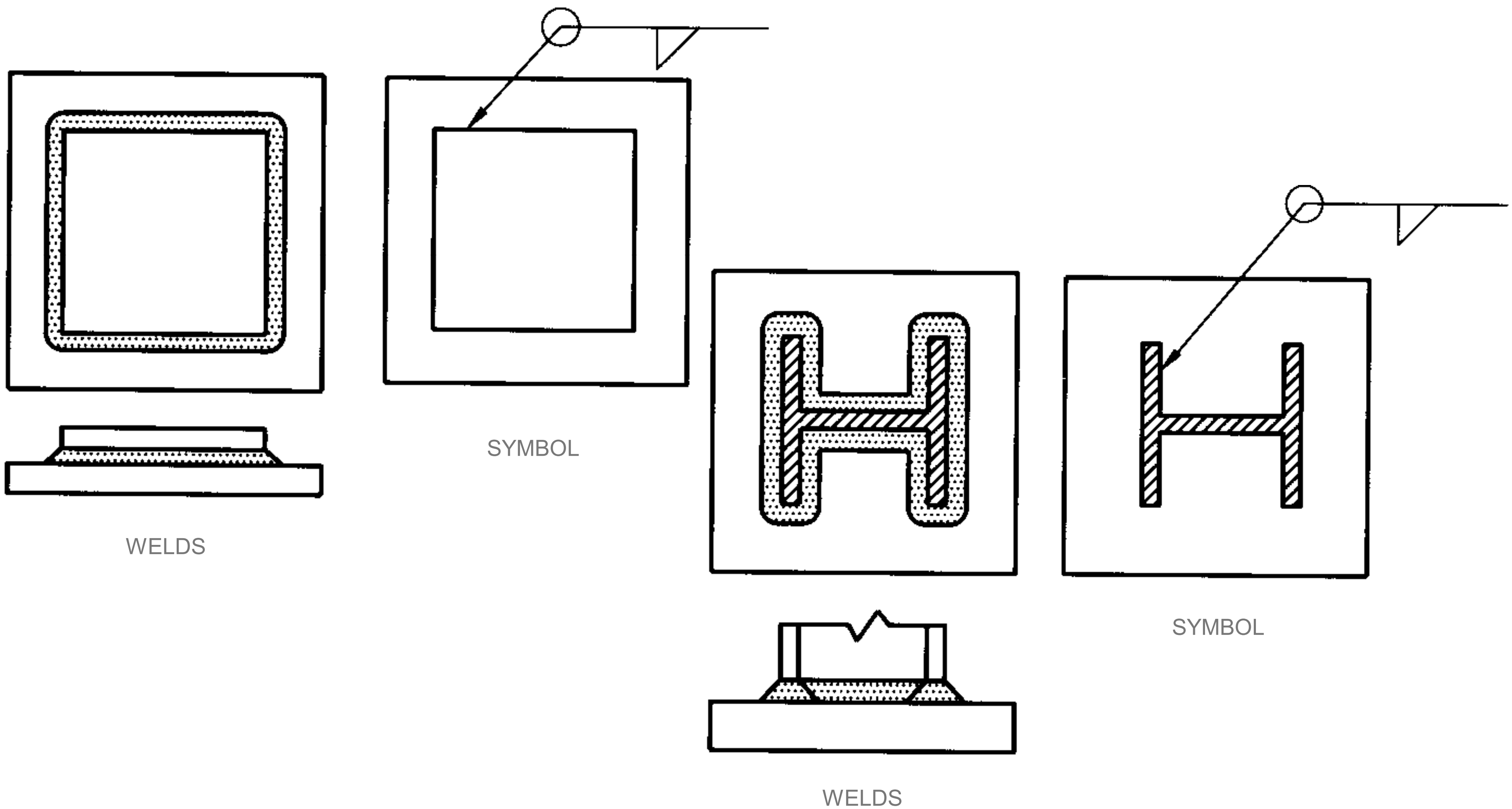
Field Weld and All-Around Symbol

- Flag indicated field weld
- Circle indicates that the is to continue along the entire joint length (i.e., weld all around)

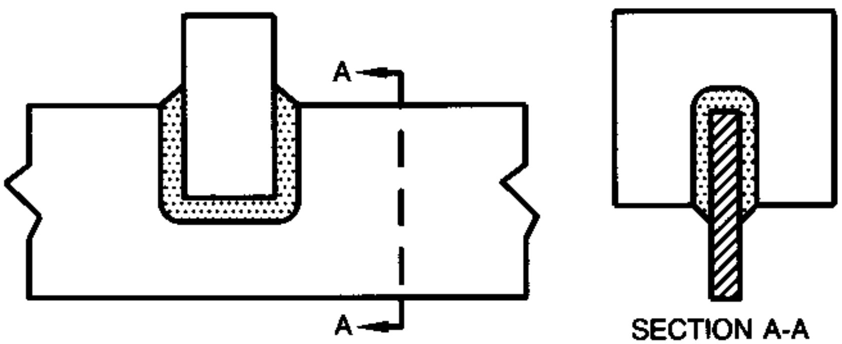


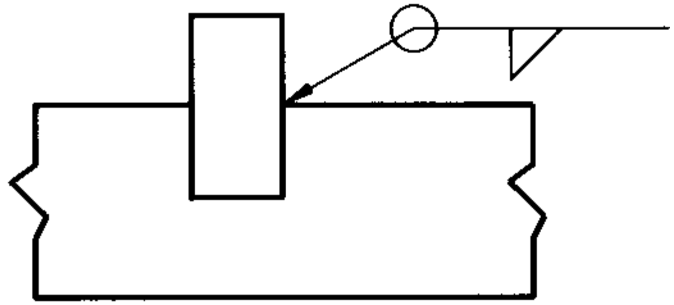


Specification of Extent of Welding Using Weld All-Around Symbol



Extent of Welding Denoted by Symbols Using Weld All-Around Symbol

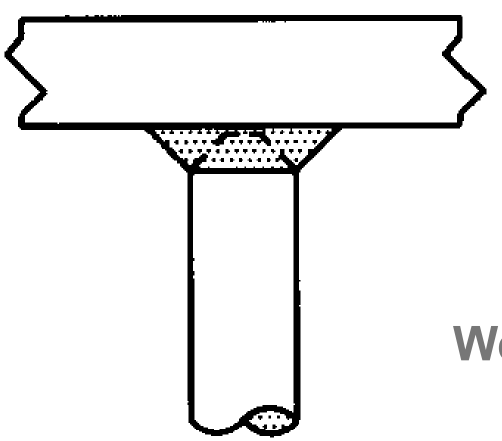




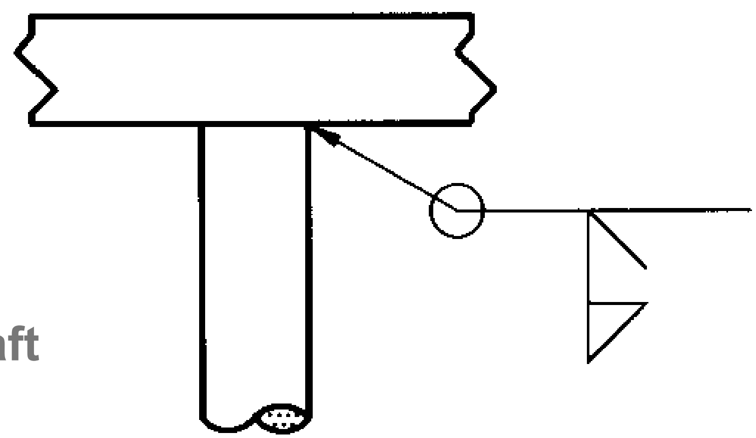
WELDS

Weld in Several Planes

SYMBOL



Weld Around a Shaft

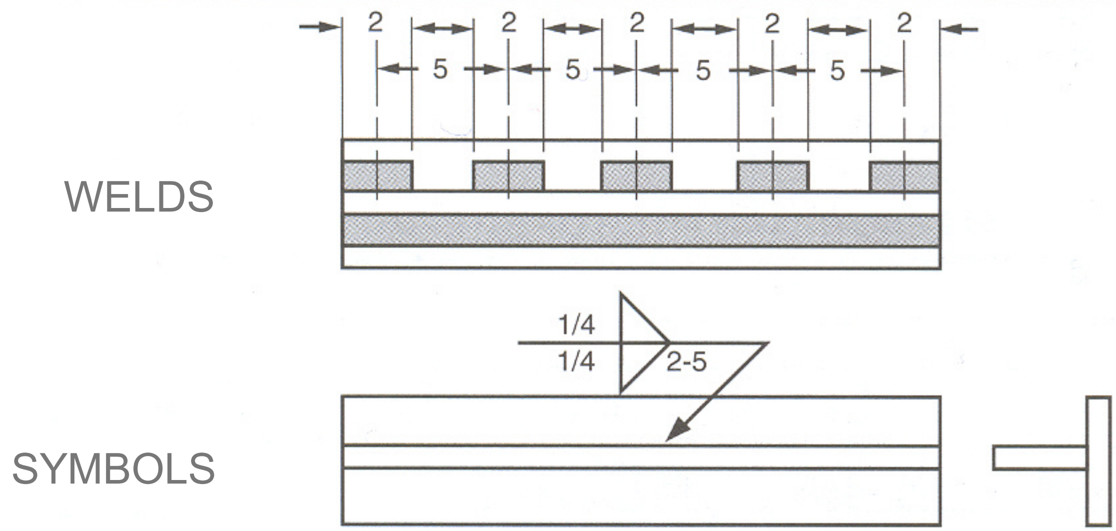


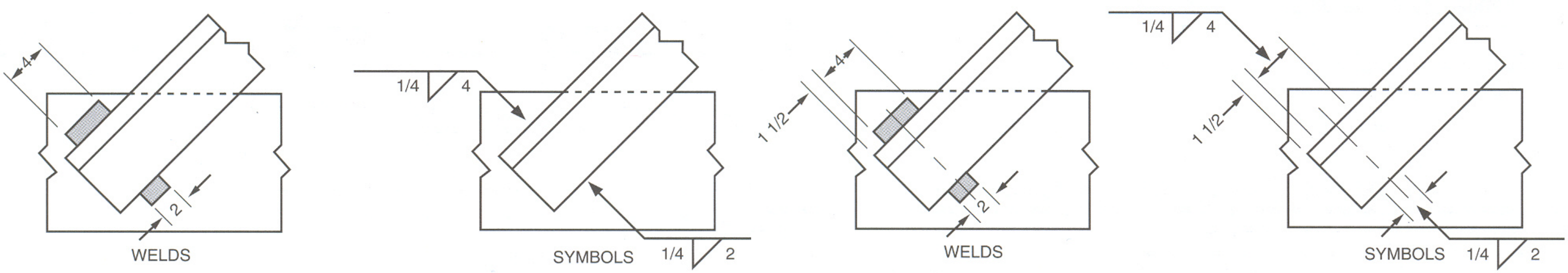
WELD

SYMBOL

Location and Extent of Fillet Welds

Size Length and Pitch



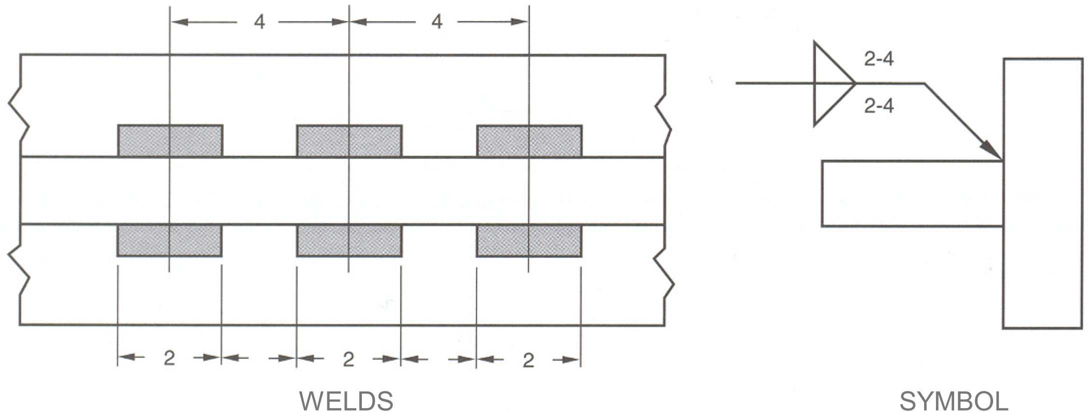


Welds Approximately Located

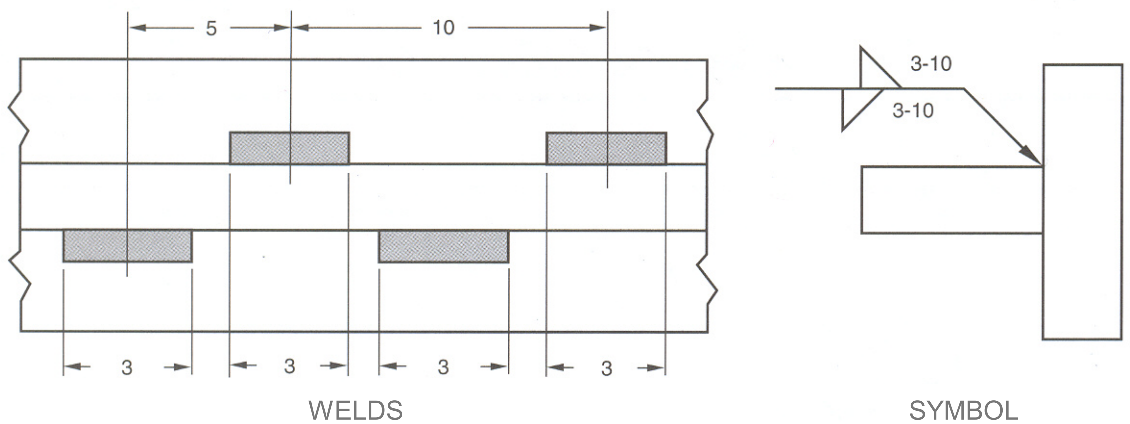
Welds Definitely Located

Length and Pitch of Intermittent Welds

Chain Intermittent Welds

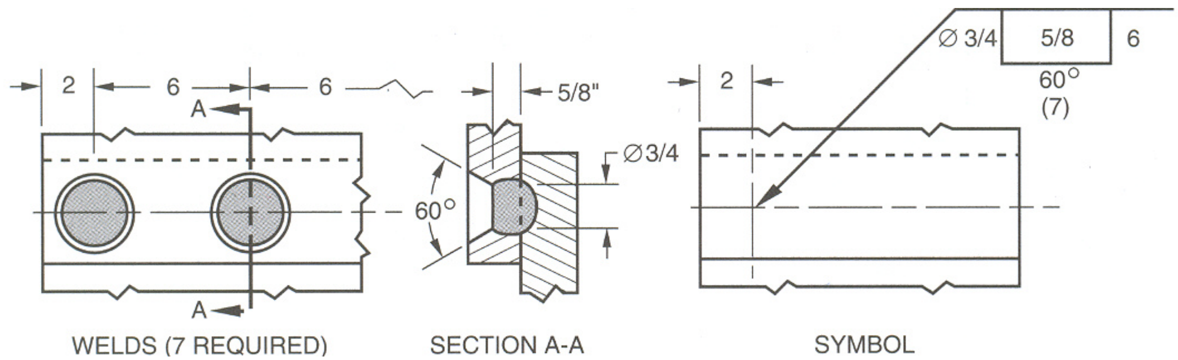


Staggered Intermittent Welds

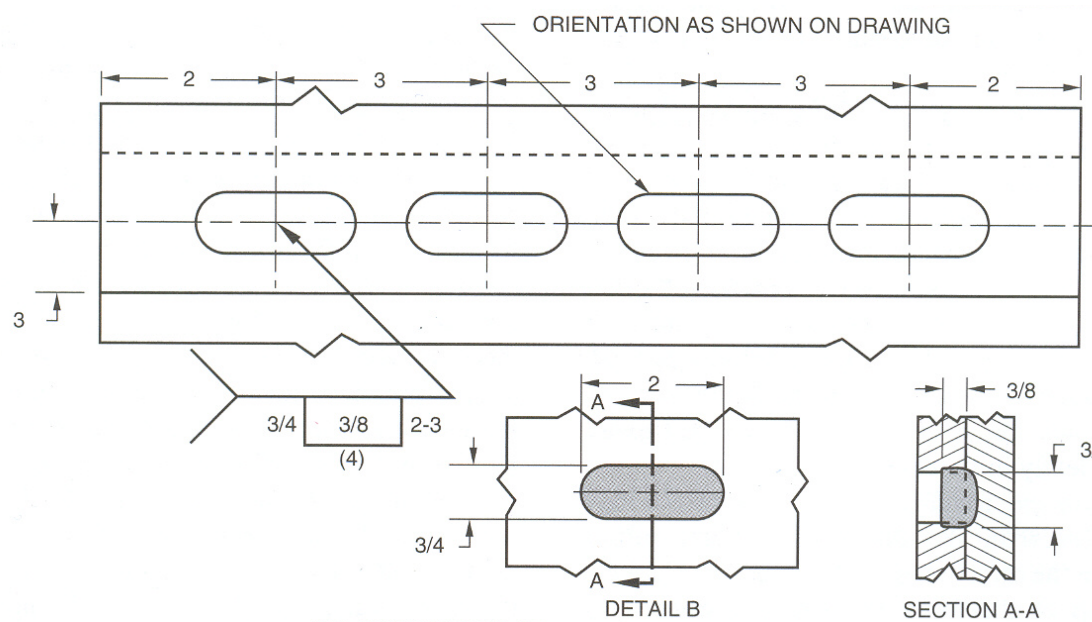


Dimensions of Plug and Slot Weld

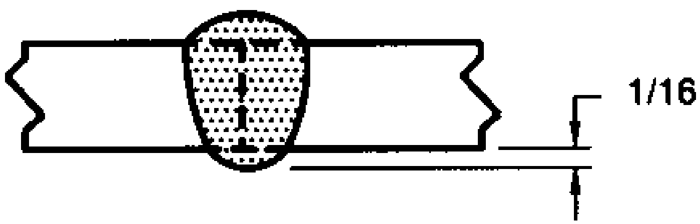
Partially Filled Plug Weld



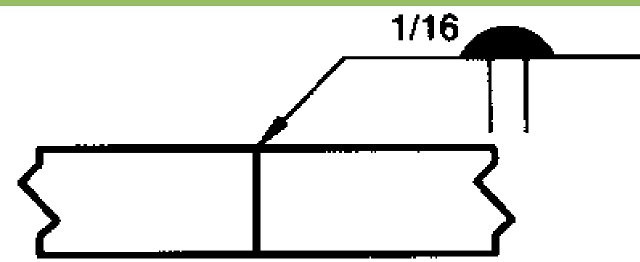
Partially Filled Slot Weld



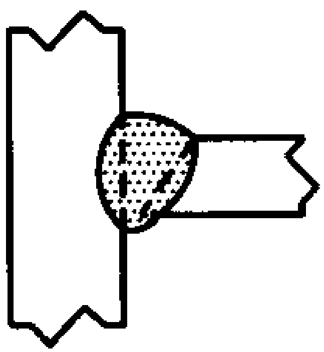
Melt-Through Symbol



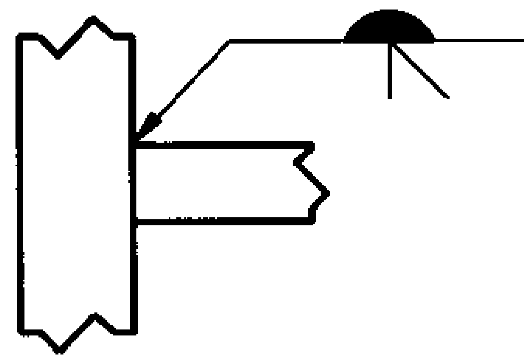
WELD CROSS SECTION



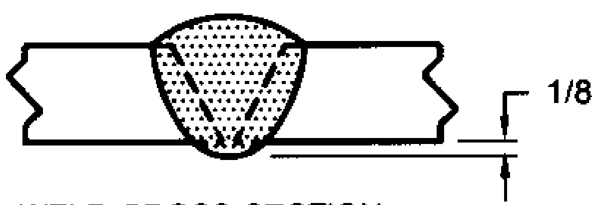
SYMBOL



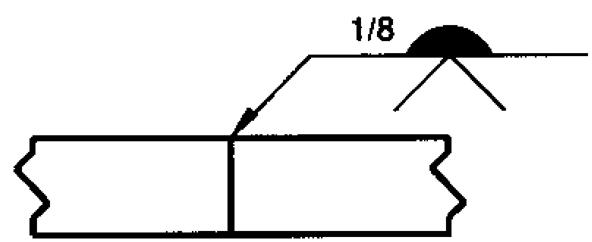
WELD CROSS SECTION



SYMBOL

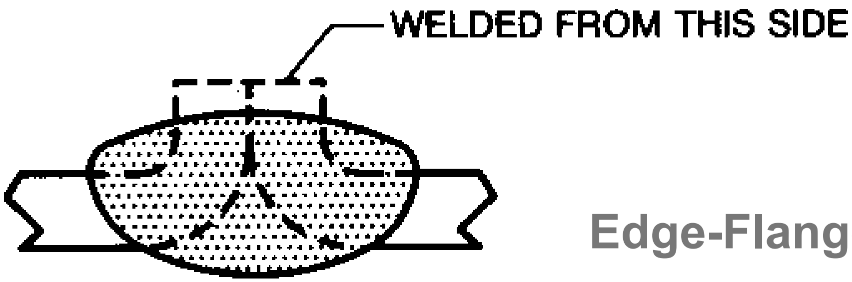


WELD CROSS SECTION

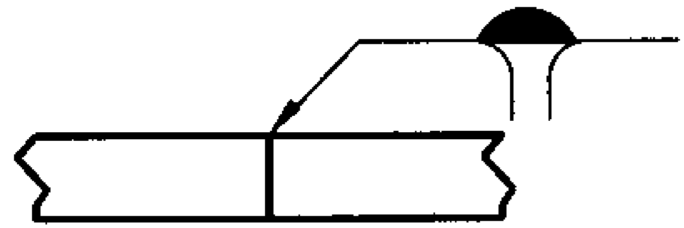


SYMBOL

Melt-Through with Flange Welds

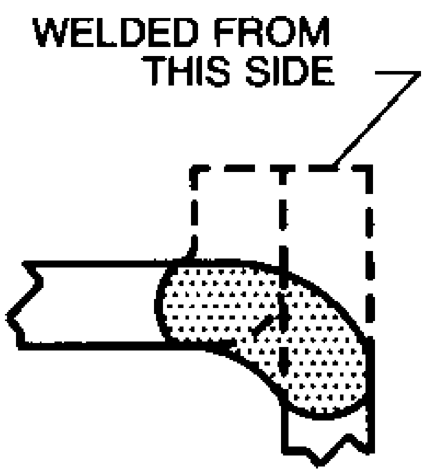


WELD CROSS SECTION

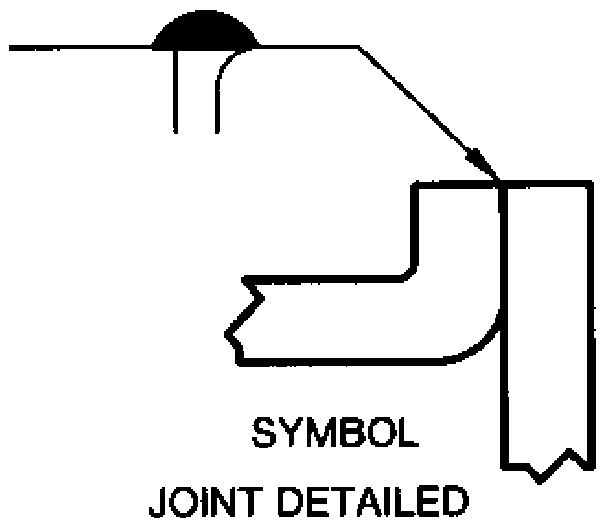


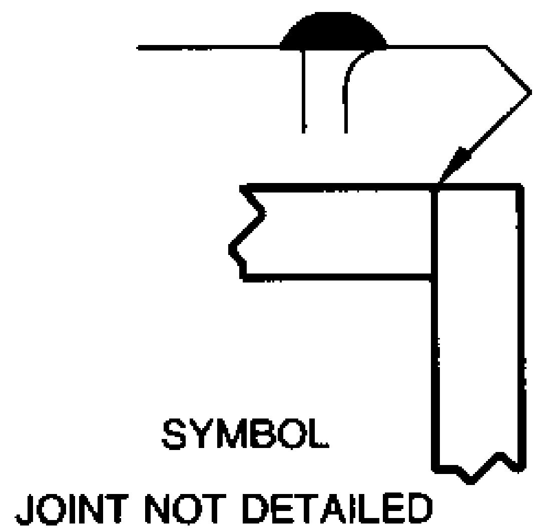
SYMBOL

Edge-Flange



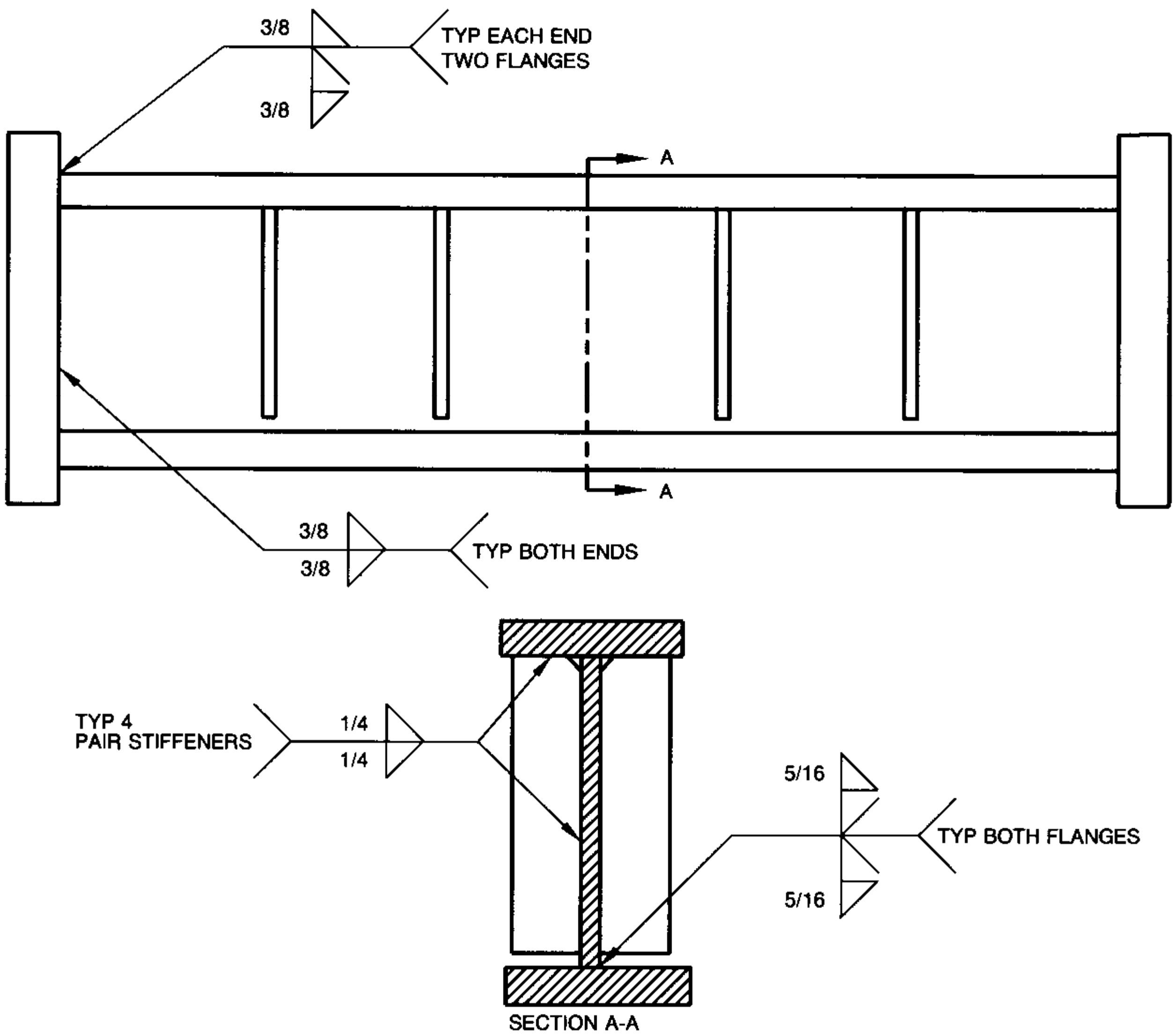
WELD CROSS SECTION



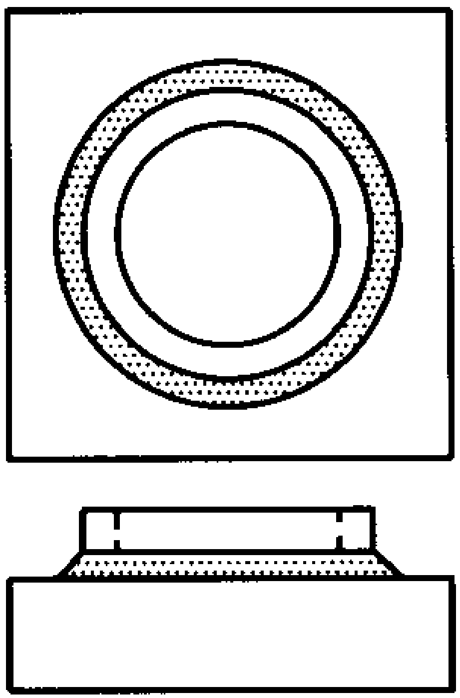


Corner-Flange

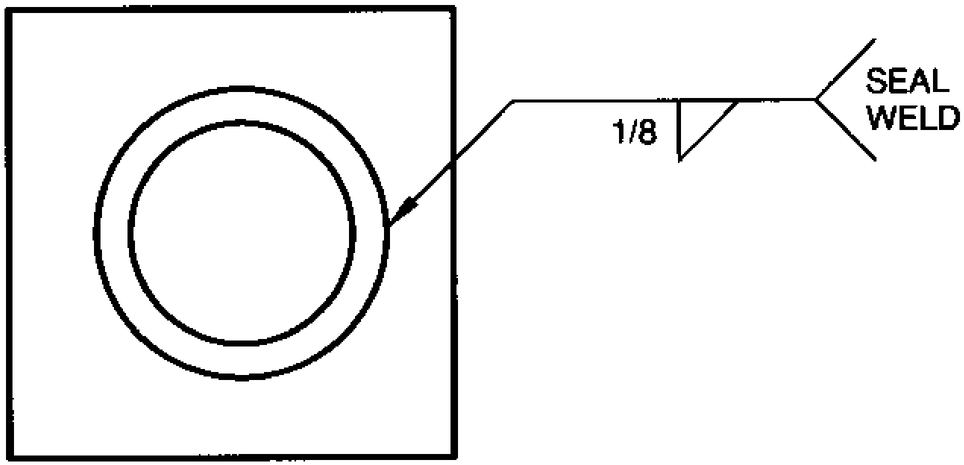
Application of "Typical" Welding Symbols Using Tail



Specification of Extent of Welding Using Tail of the Welding Symbol



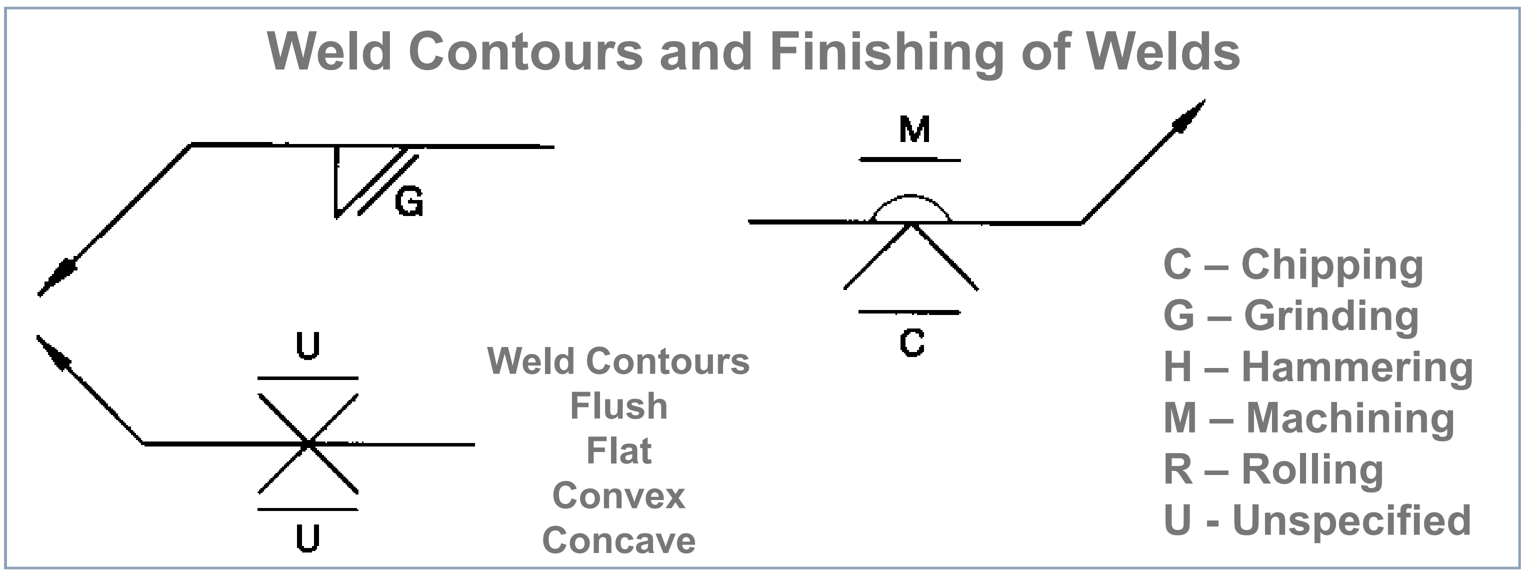
WELD



SYMBOL

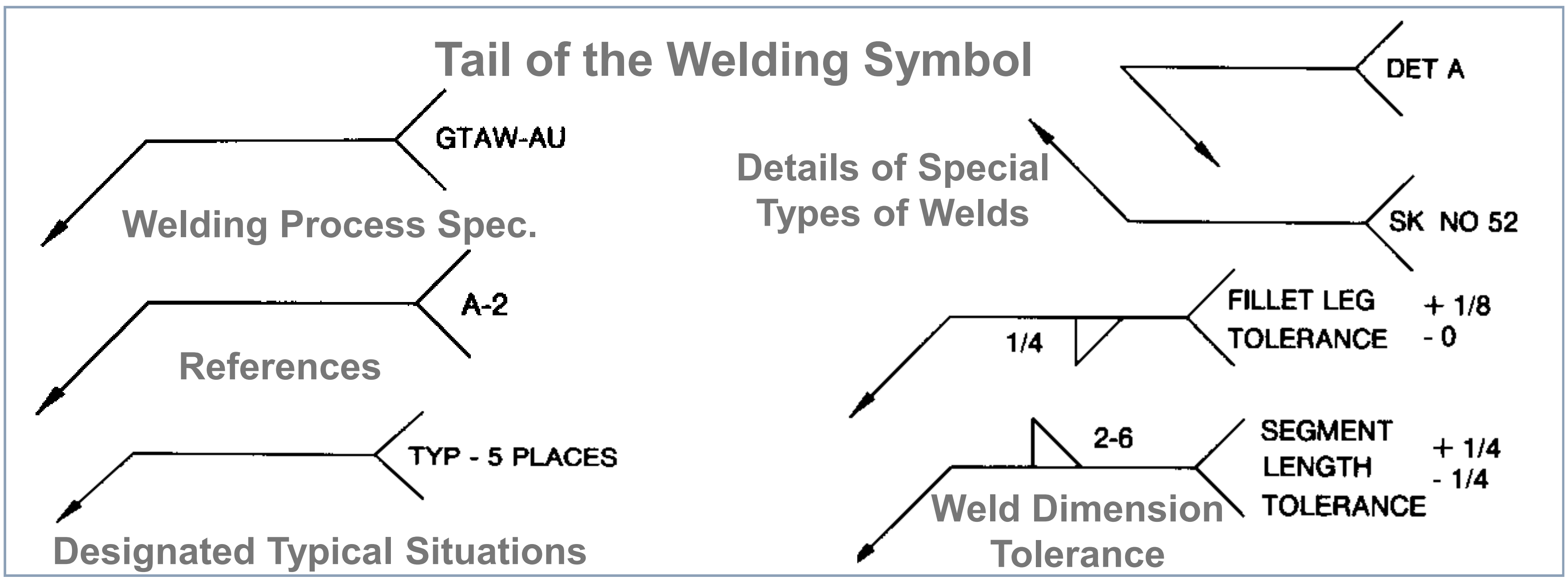
Specification of Completed Weld Using the Welding Symbol

- The weld tail can specify the final contour of the weld as well as any addition processing steps require to achieve the contour

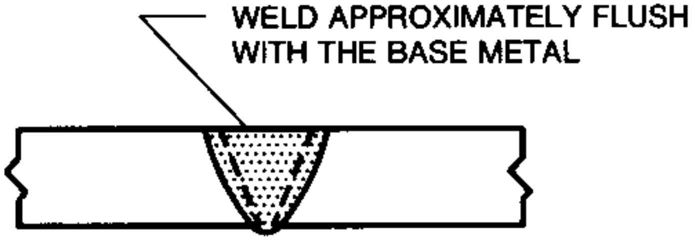


Supplementary Information

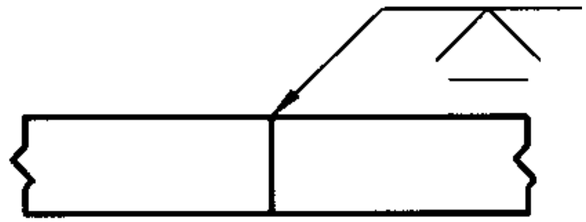
- The weld tail can also include supplementary information important the welder/supervisor
  - Welding procedure
  - Additional/specific welding dimensions or tolerances



Flush and Convex Contour Symbols

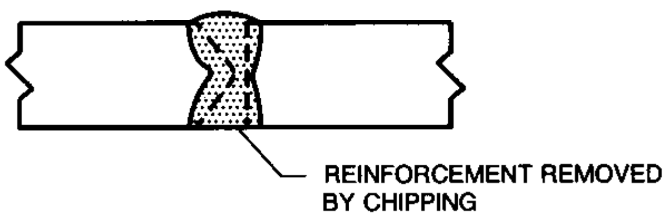


WELD CROSS SECTION

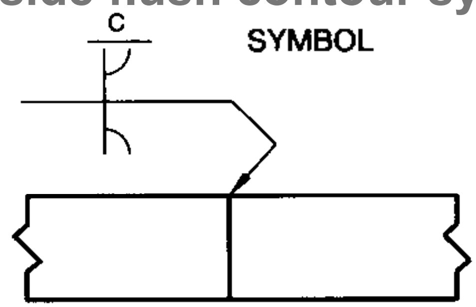


Arrow side flush contour symbol

SYMBOL

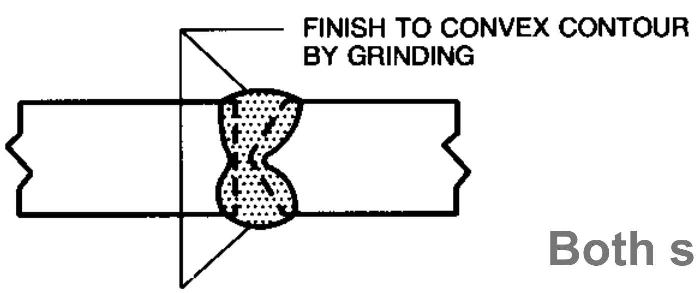


WELD CROSS SECTION

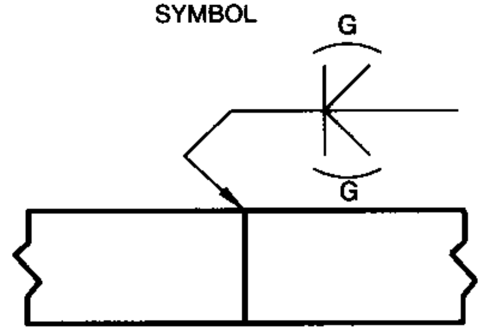


Other side flush contour symbol

SYMBOL



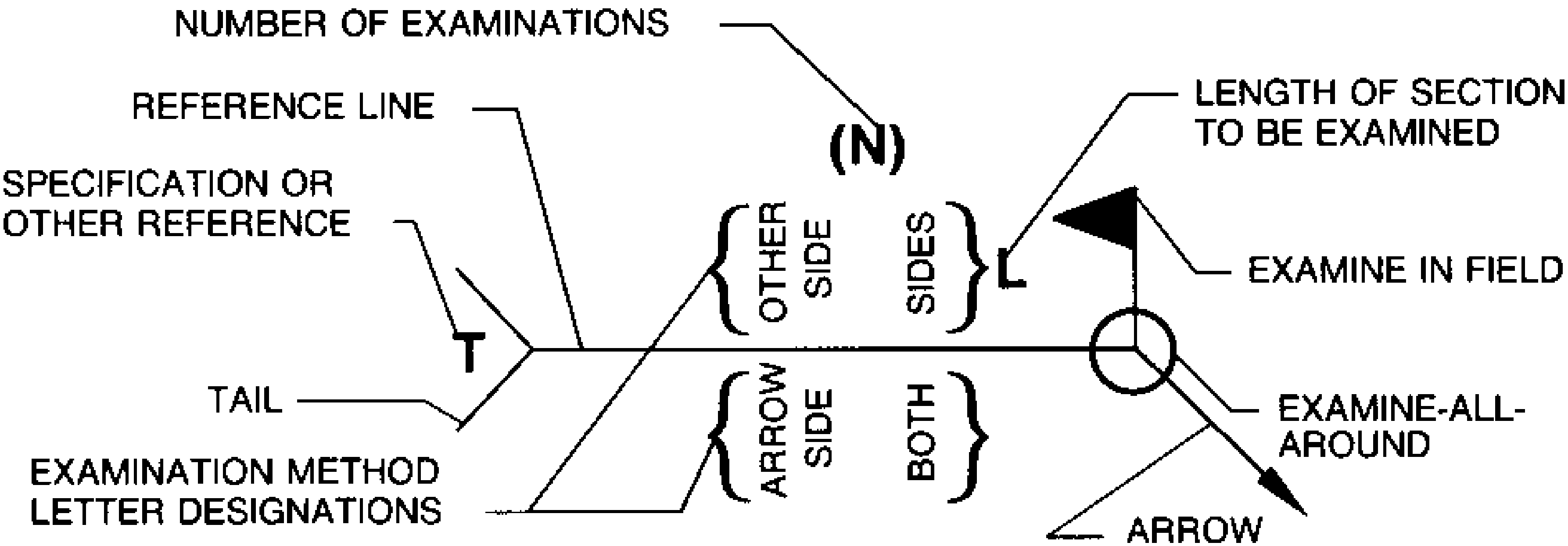
WELD CROSS SECTION

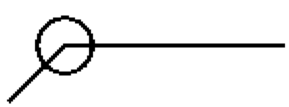
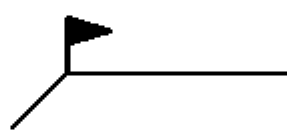
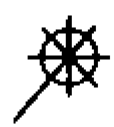


Both sides convex contour symbol

SYMBOL

Standard Location of NDE Elements



EXAMINE ALL AROUND	FIELD EXAMINATION	RADIATION DIRECTION
		

Standard Location of NDE Elements

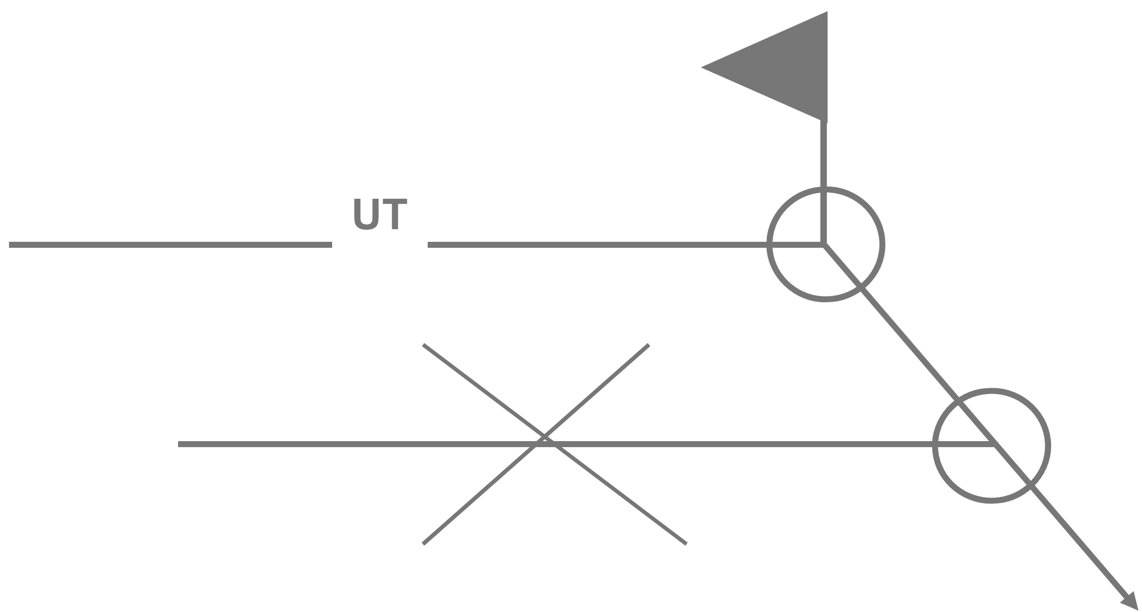
- The NDE Key elements are similar to the welding key elements
  - Reference Line
  - Arrow
  - Examination Method Letter Designations
  - Extent and Number of Examinations
  - Supplementary Symbols
  - Tail (specifications, codes or other references)

Examination Method Letter Designations

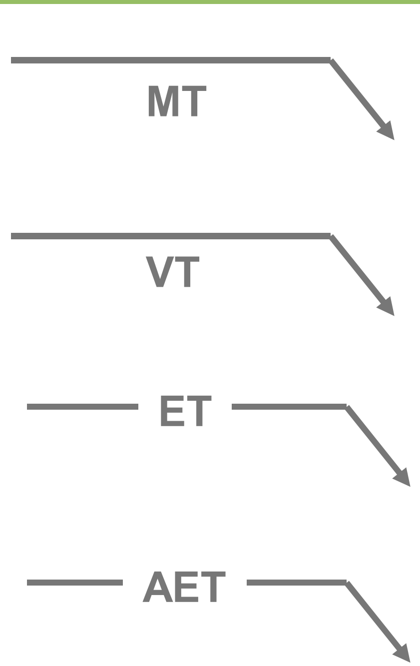
Acoustic emission	AET
Electromagnetic	ET
Leak	LT
Magnetic practical	MT
Neutron radiographic	NRT
Penetrant	PT
Proof	PRT
Radiographic	RT
Ultrasonic	UT
Visual	VT

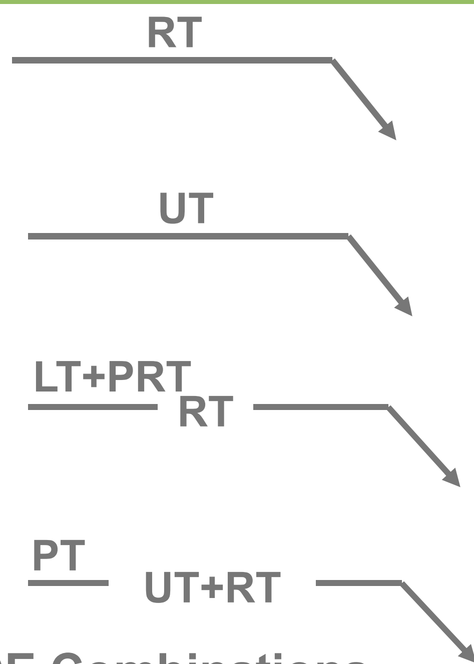
Combined Welding and NDE Symbols

- Welding and NDE symbols can be combined on the same reference line, or on separate multiple reference lines
- Combining welding and NDE symbols on multiple reference lines often clarifies the exact sequence of operations required

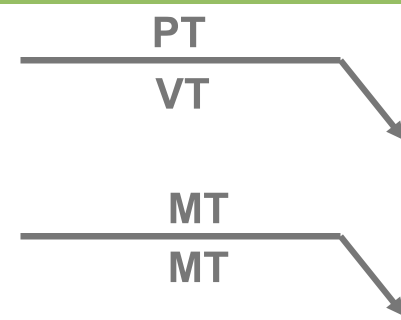


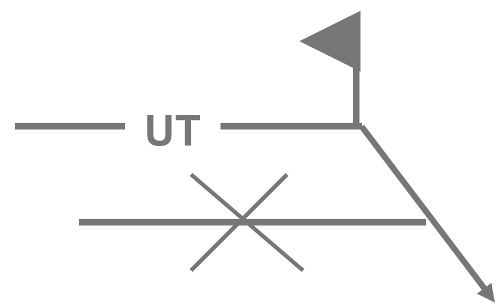
NDE Locations



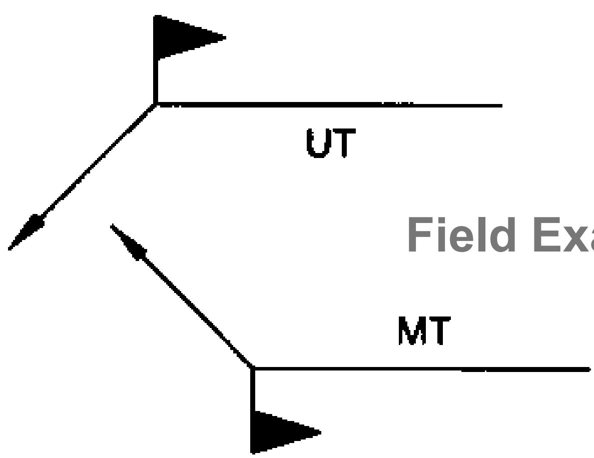


NDE Combinations

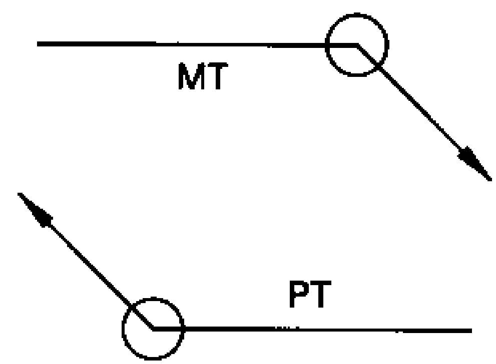




Welding & NDE Symbols



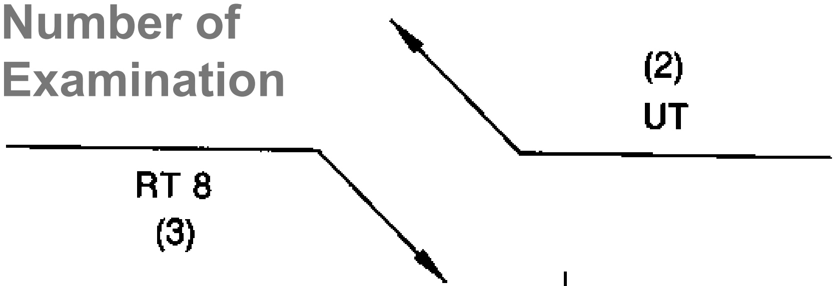
Field Examination

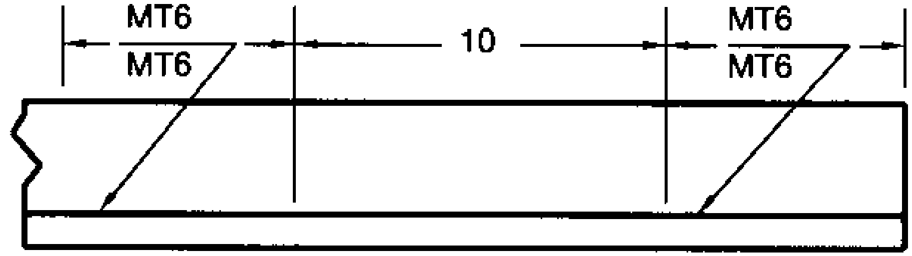


Examine-All-Around

Examples of NDE Symbols

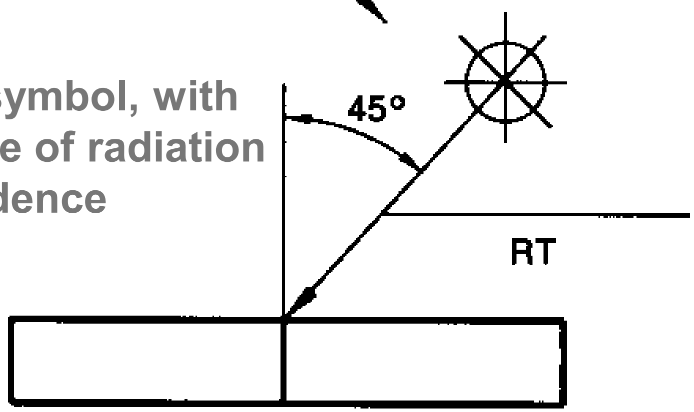
Number of Examination



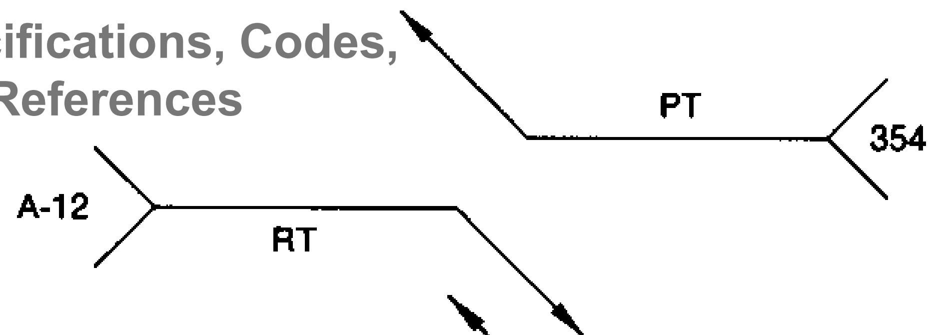


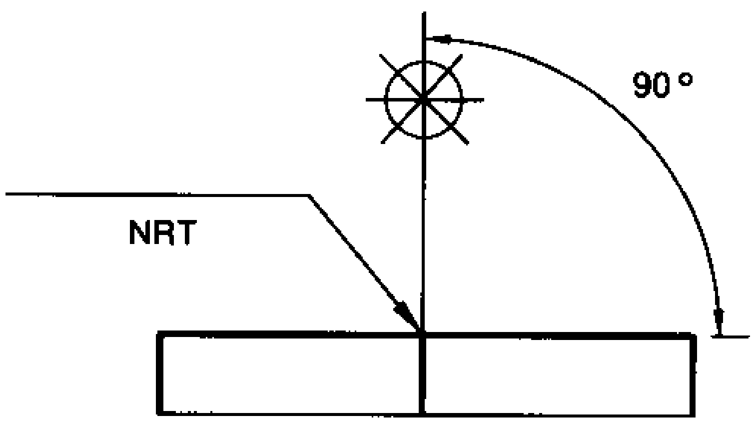
MT symbol, both sides for 6 inch length

RT symbol, with angle of radiation incidence



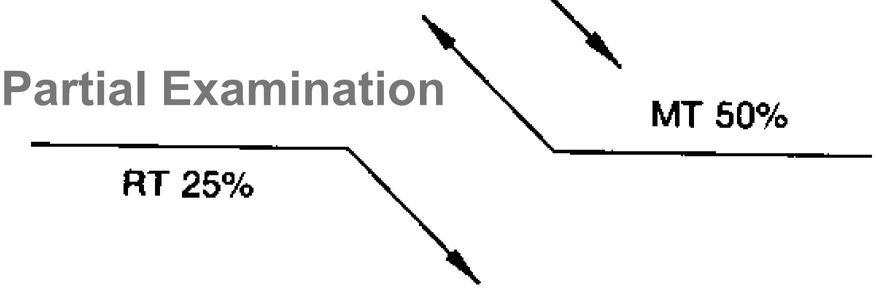
Specifications, Codes, and References





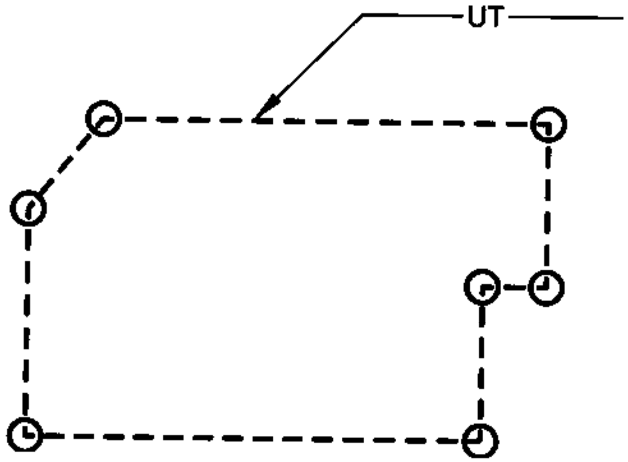
Length to be Examined

Partial Examination

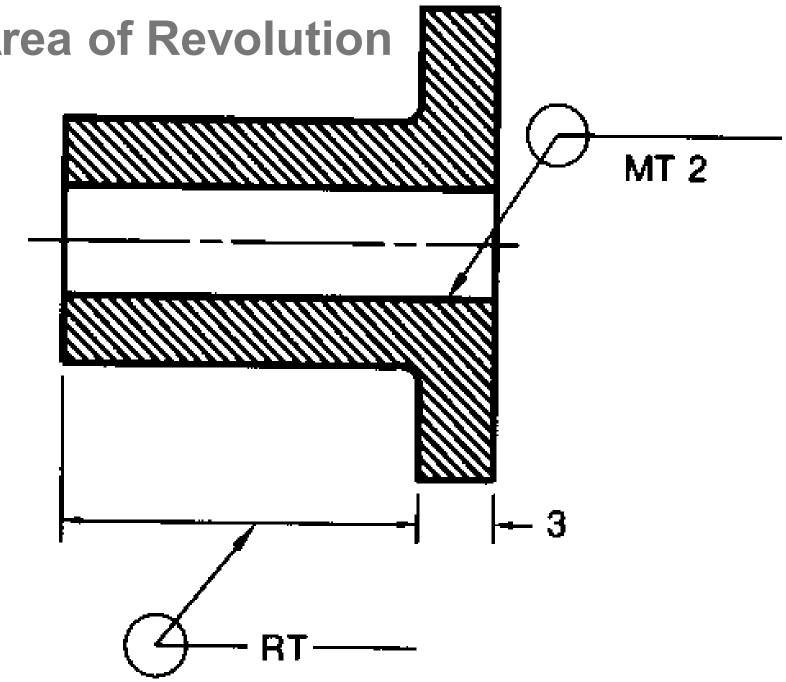


Examples of NDE Symbols

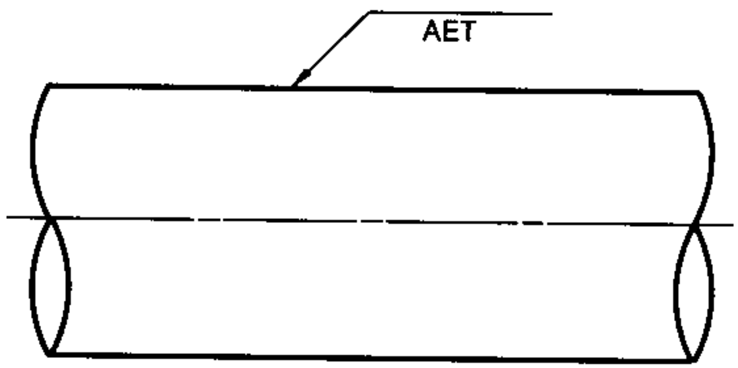
Plane Areas



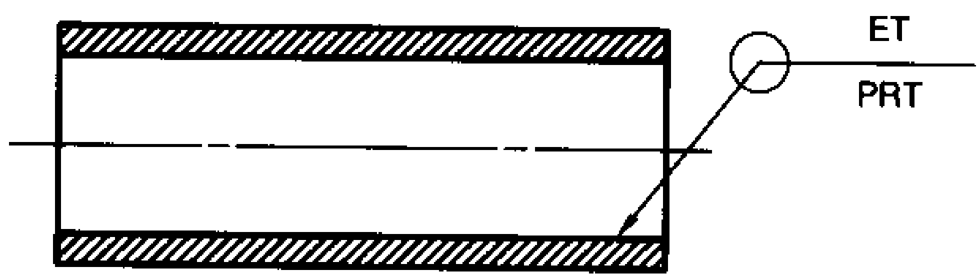
Area of Revolution



Acoustic Emission

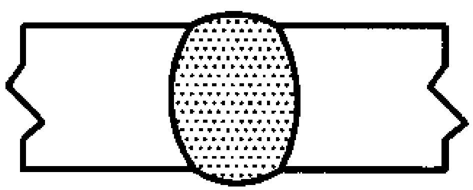


Area of Revolution

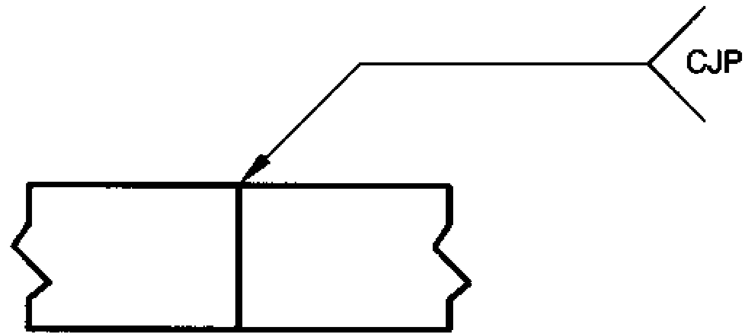


Welding Symbol Applications

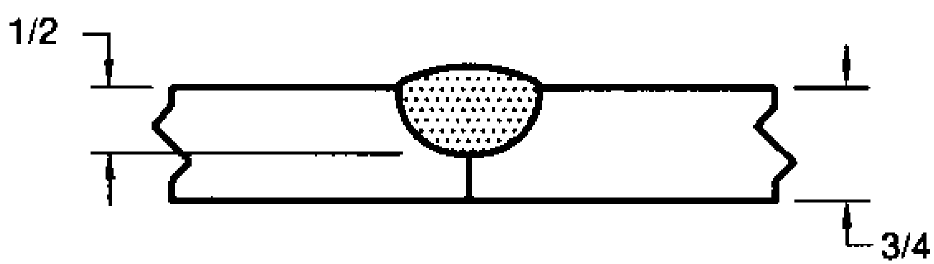
Complete Joint Penetration with Optional Joint Geometry



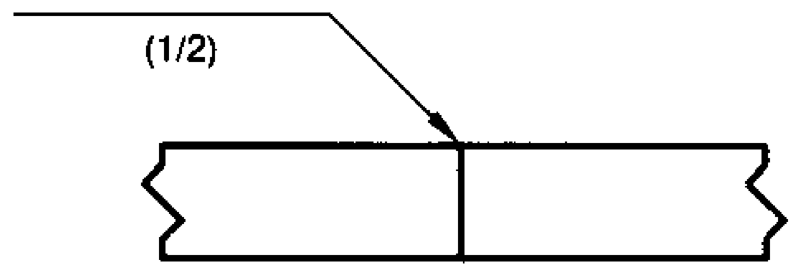
WELD CROSS SECTION



SYMBOL

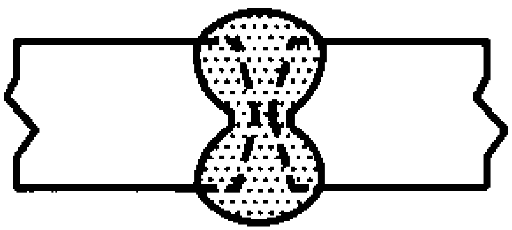


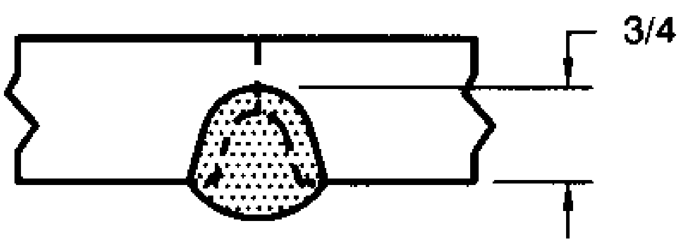
WELD CROSS SECTION



SYMBOL

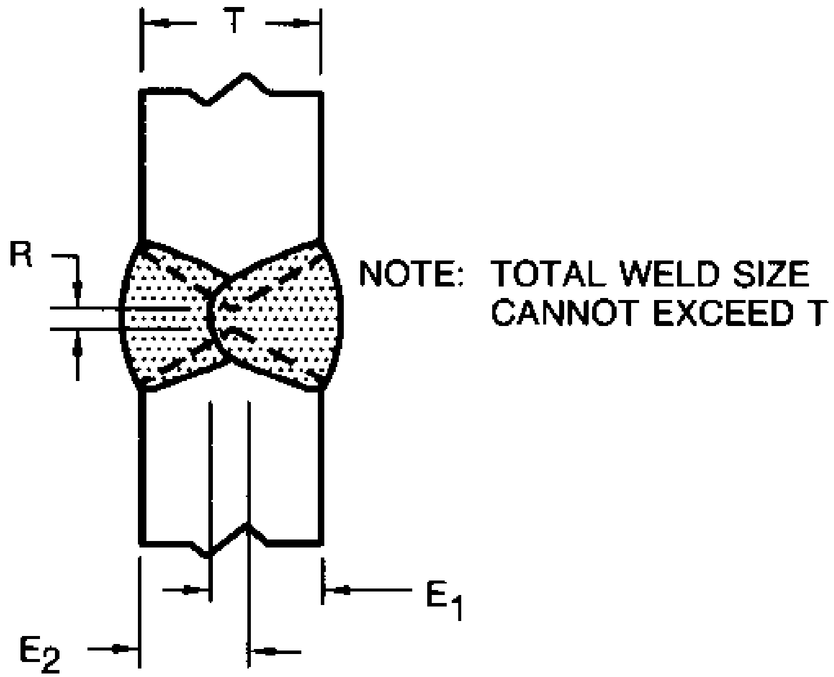
Groove Weld Size & Depth of Bevel Not Specified


WELD CROSS SECTION

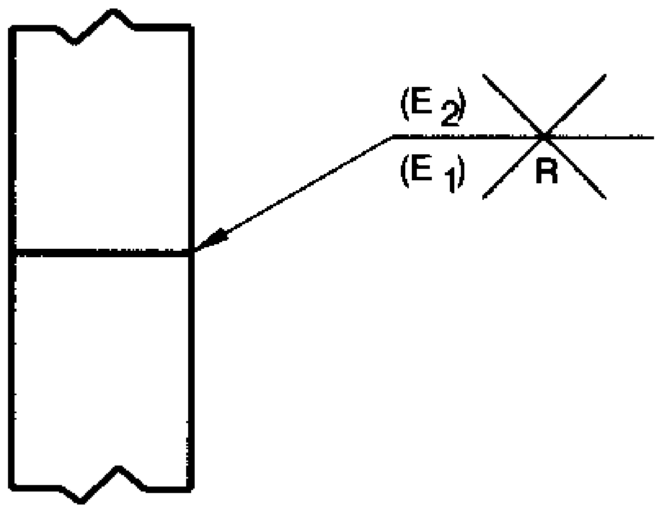


WELD CROSS SECTION

Specification of Groove Weld Size (E) Only



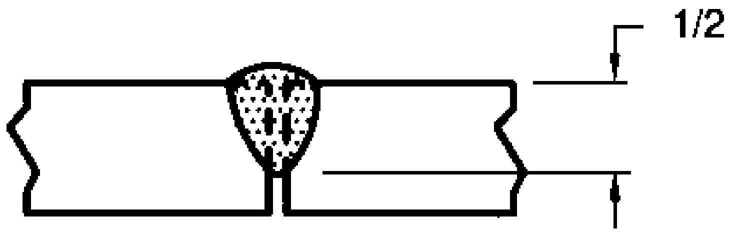
WELD CROSS SECTION



SYMBOL

Double-V-groove weld with root opening

Groove Weld Size without Depth of Bevel Specified



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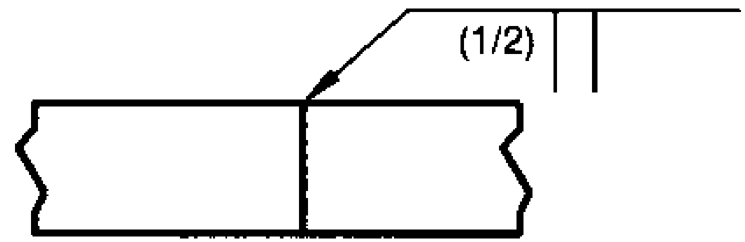
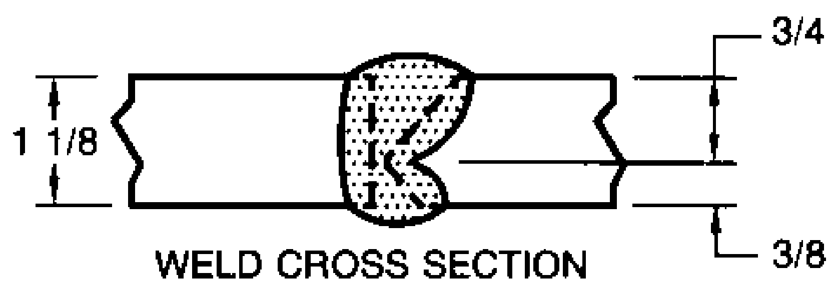


SYMBOL



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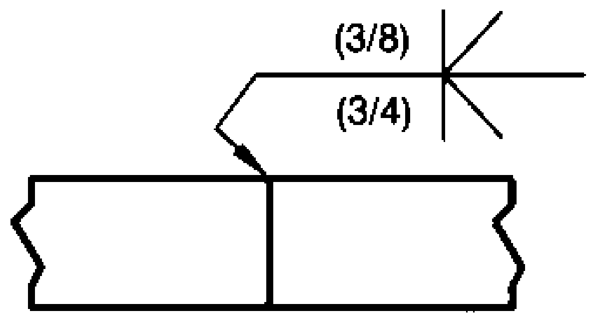
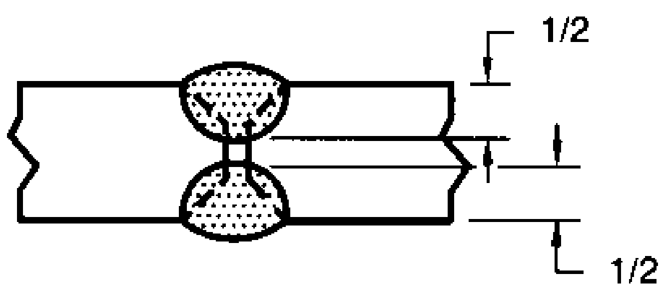
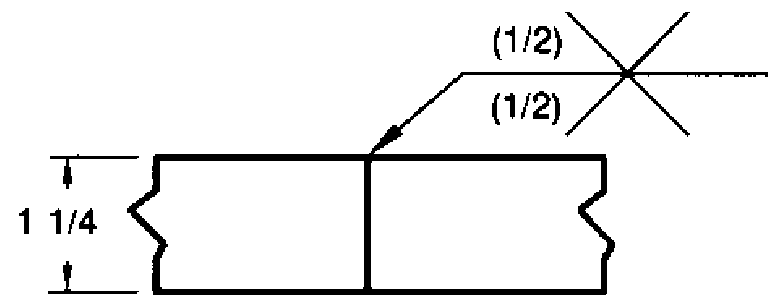


SYMBOL

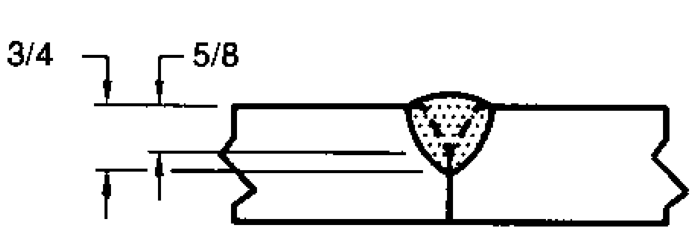


WELD CROSS SECTION



SYMBOL

Specification of Groove Weld Size (E) and Depth of Bevel (S)



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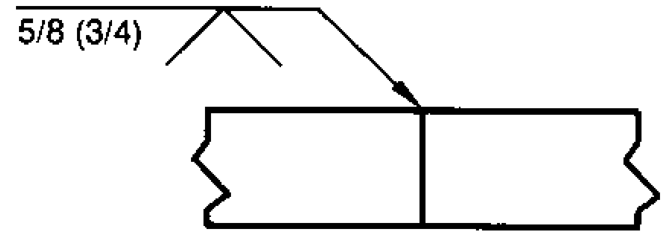

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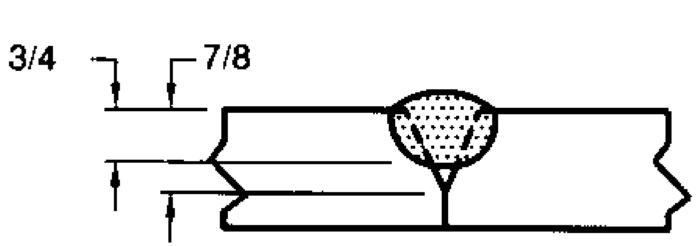

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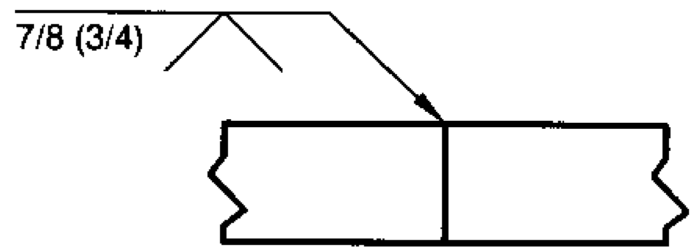

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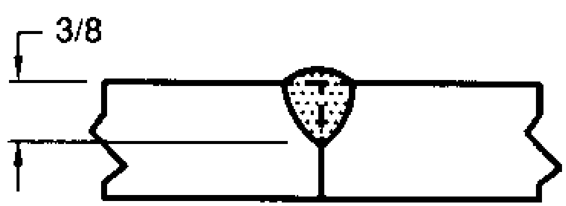

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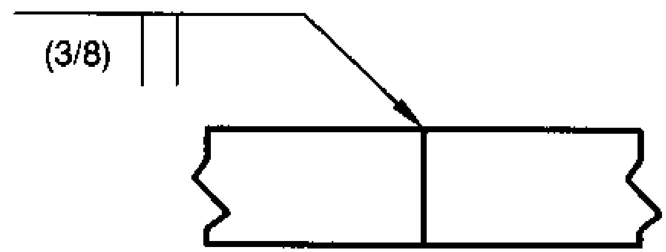
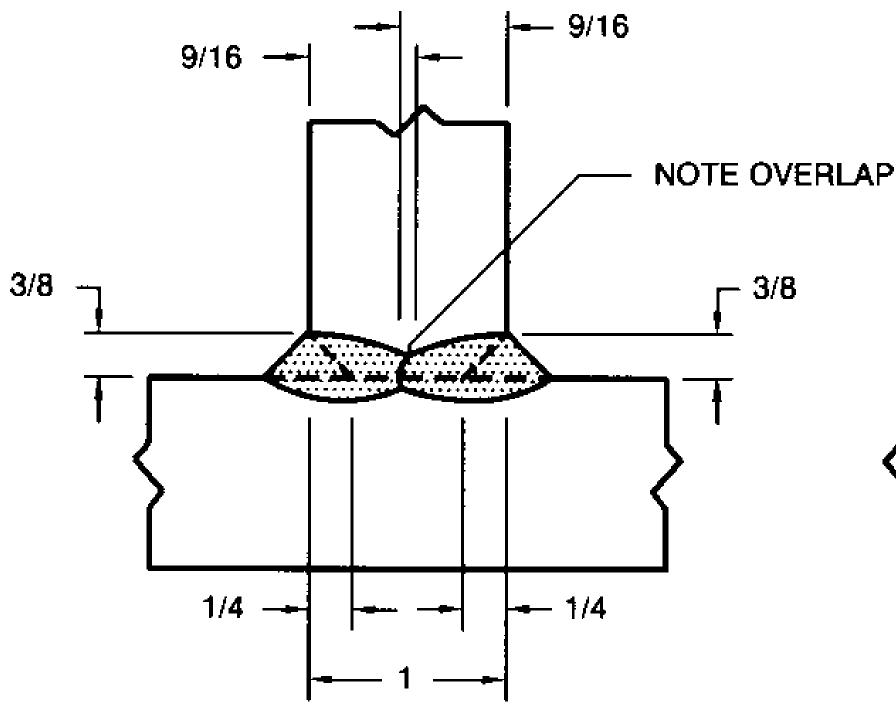
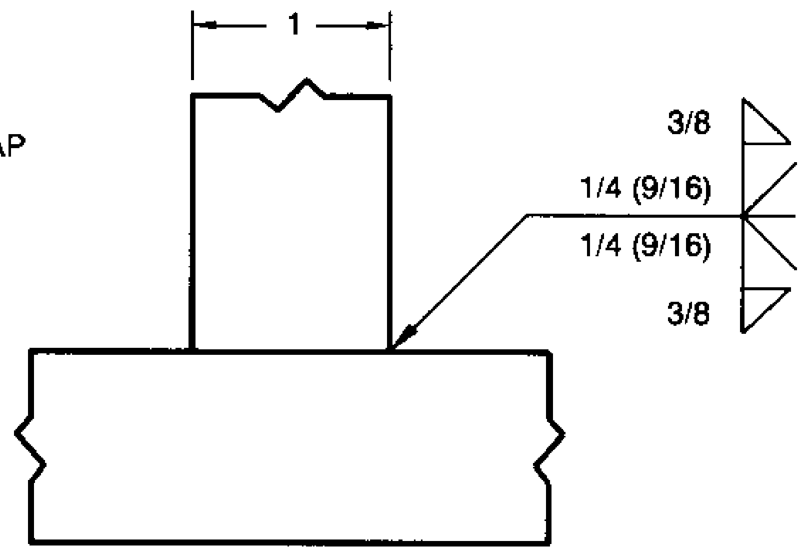


SYMBOL

Combined Groove and Fillet Welds



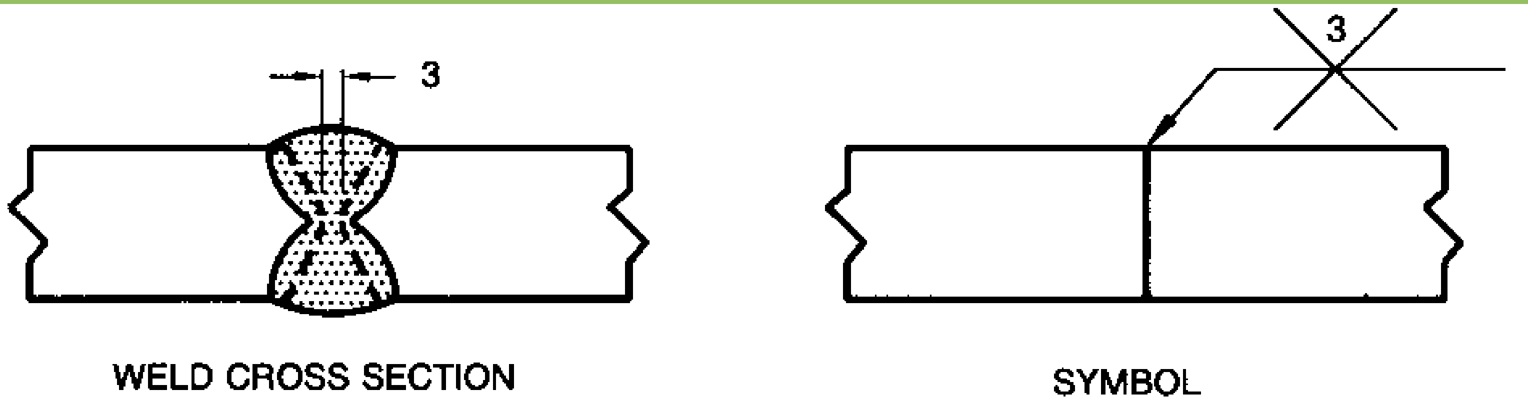
WELD CROSS SECTION

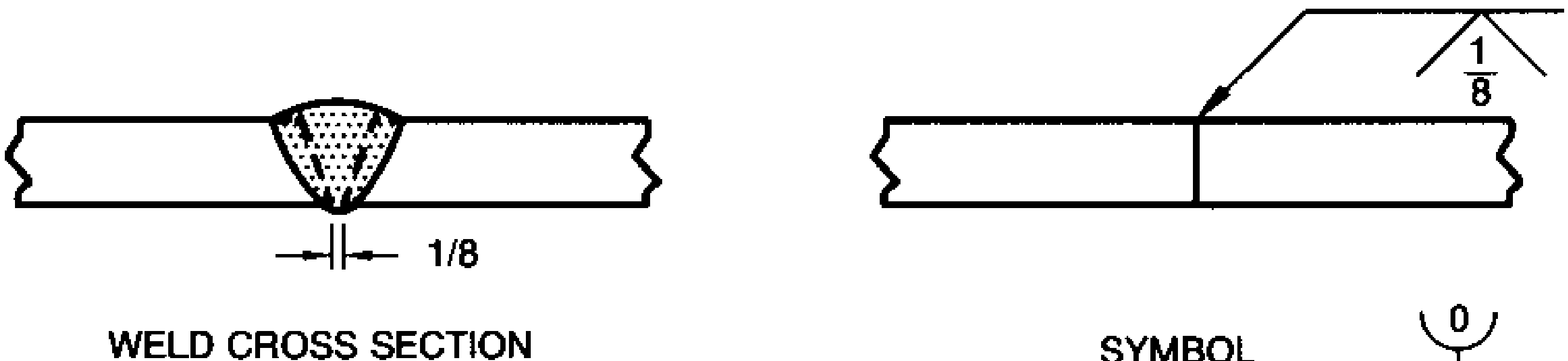


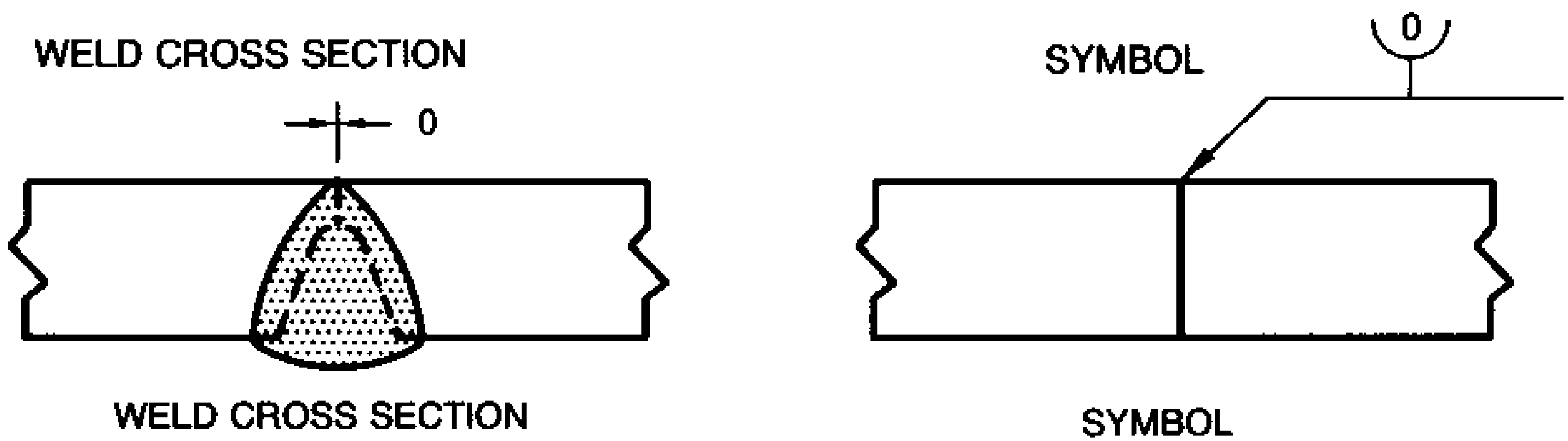
SYMBOL

NOTE: TOTAL GROOVE WELD SIZE CANNOT EXCEED 1

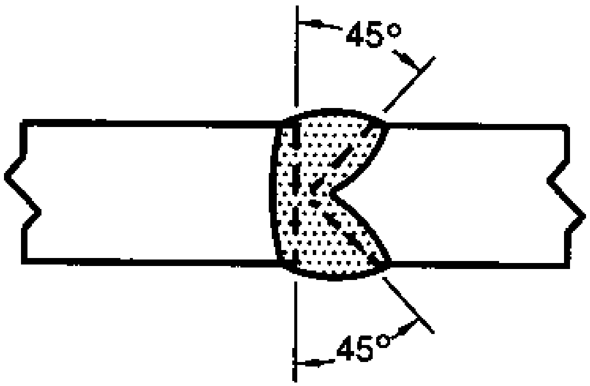
Root Opening of Groove Welds



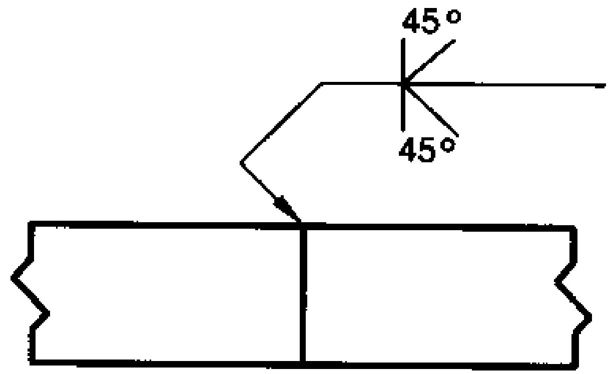




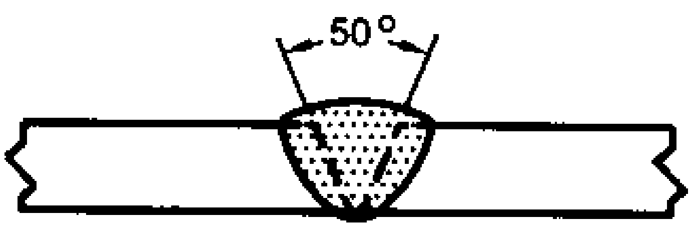
Groove Angle of Groove Welds



WELD CROSS SECTION



SYMBOL



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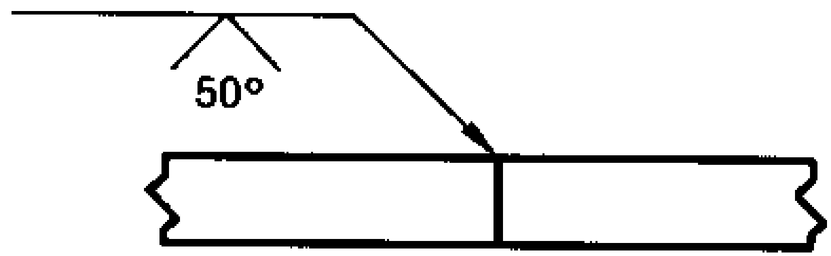
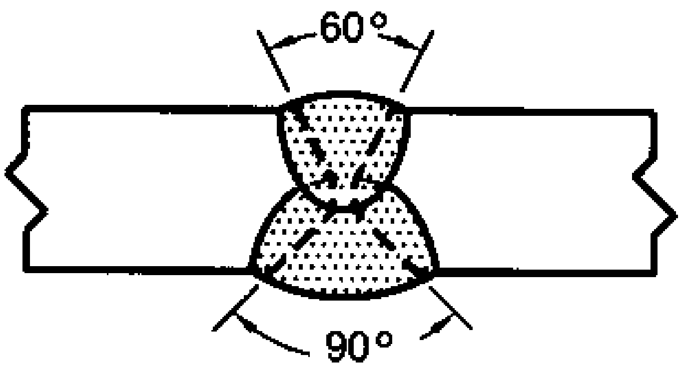


SYMBOL

Groove angle is placed just outside the weld symbol

Groove Angle of Groove Welds



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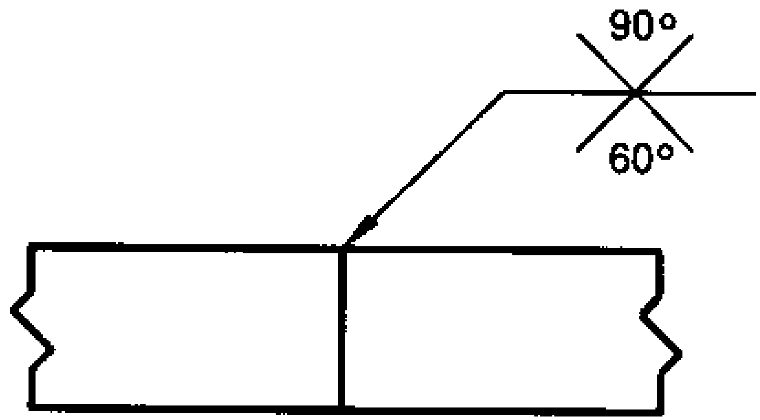
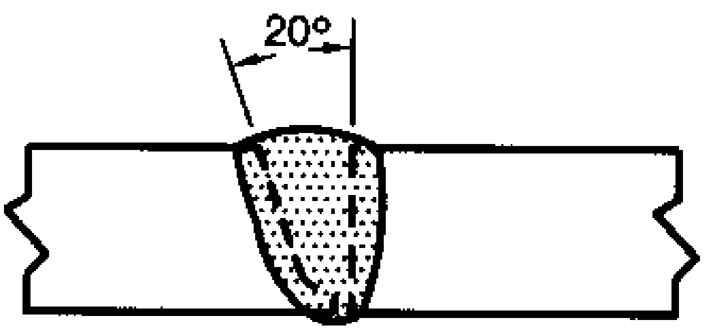


SYMBOL



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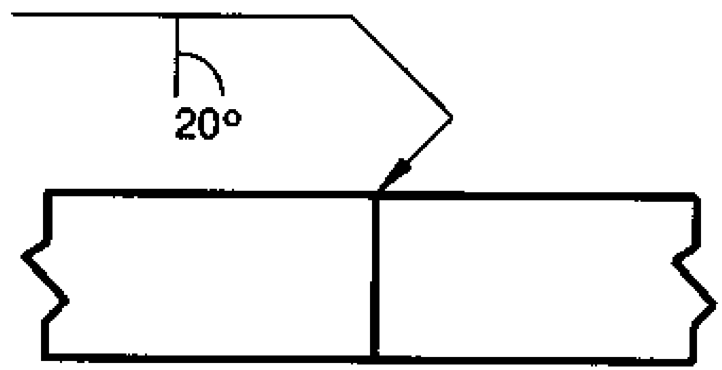
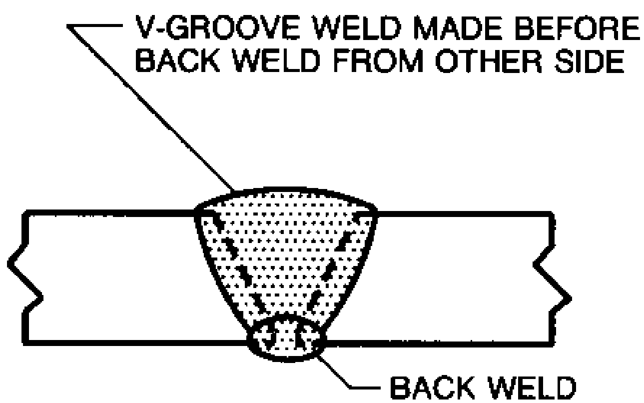


SYMBOL

Back or Backing Weld Symbol



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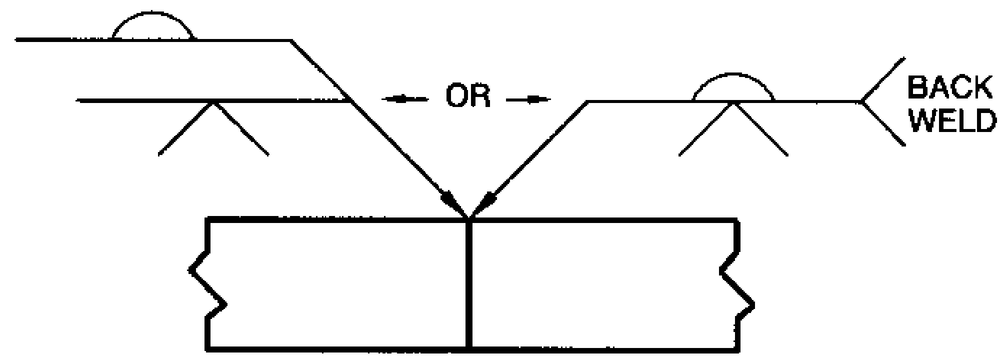
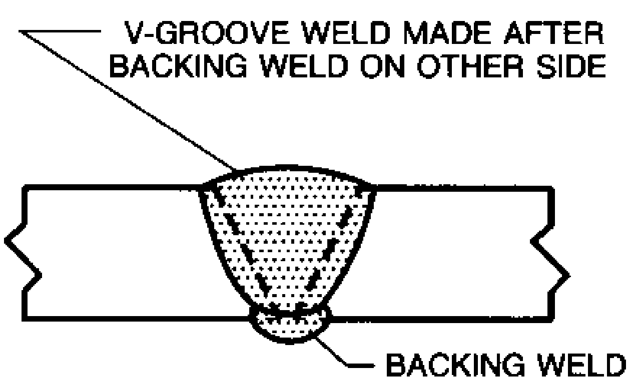
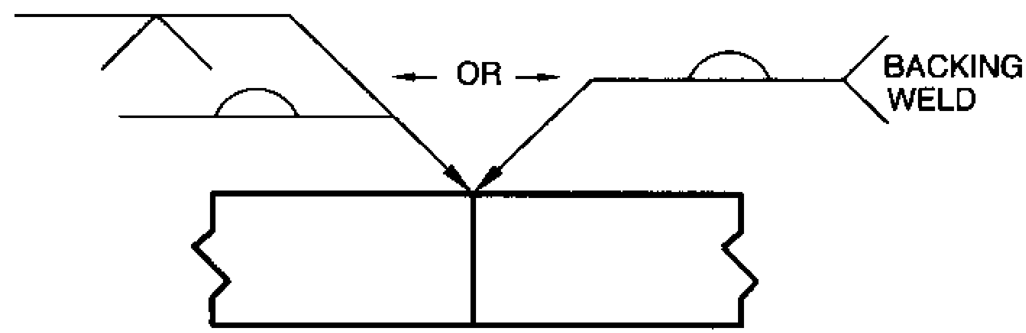


Back Weld Symbol

SYMBOL



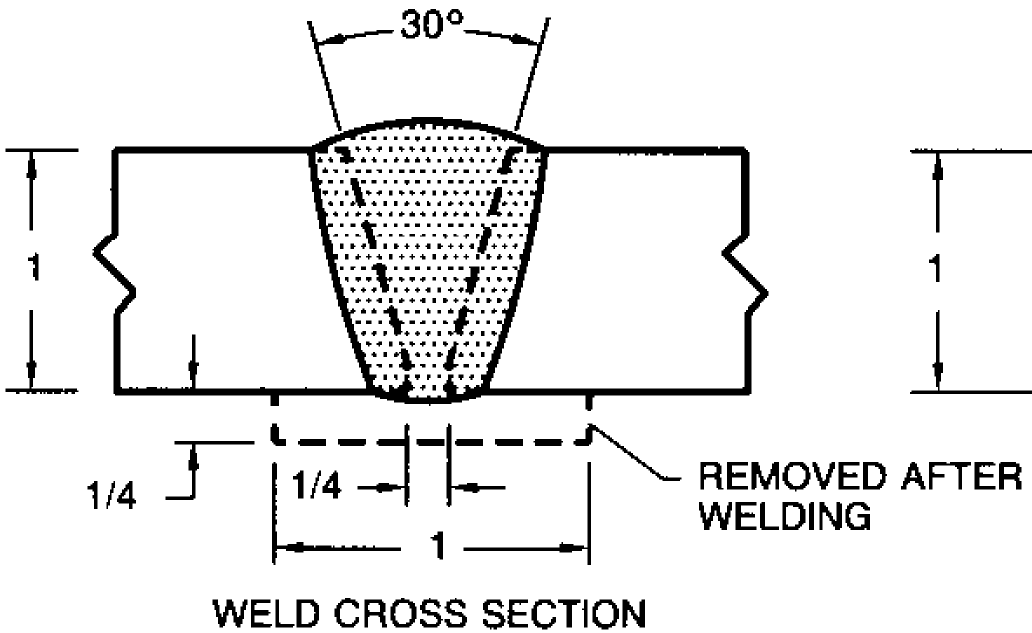
WELD CROSS SECTION

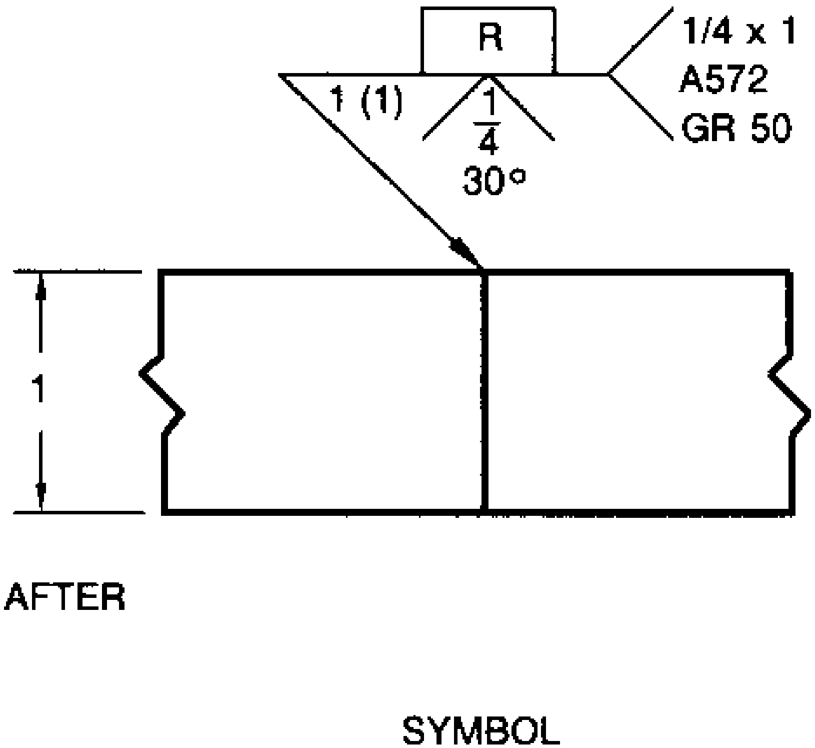


Backing Weld Symbol

SYMBOL

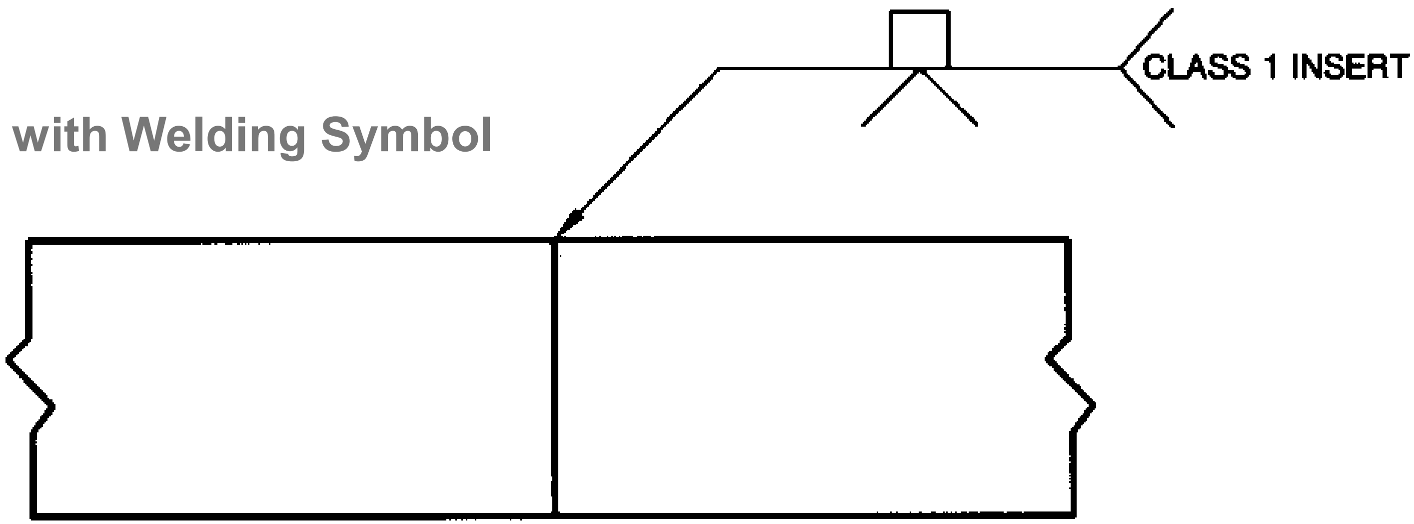
Single-V-Groove Weld with Backing

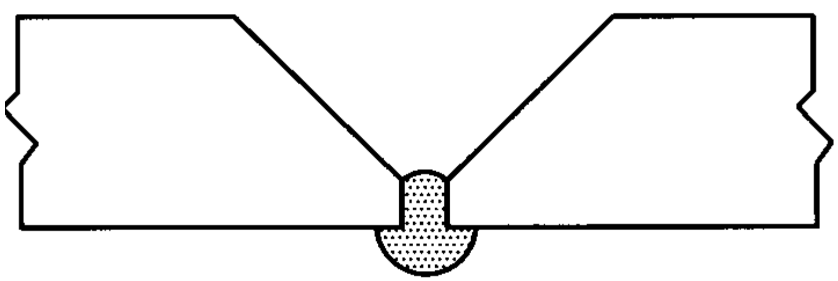




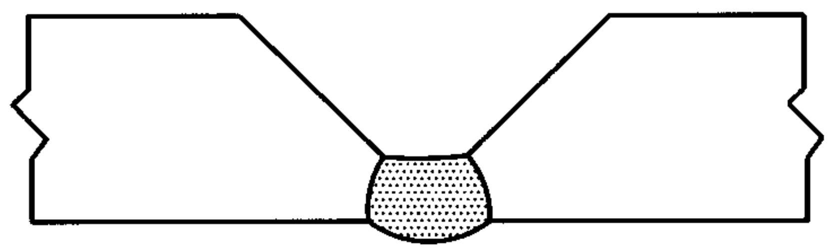
Application of the Consumable Insert Symbol

Joint with Welding Symbol



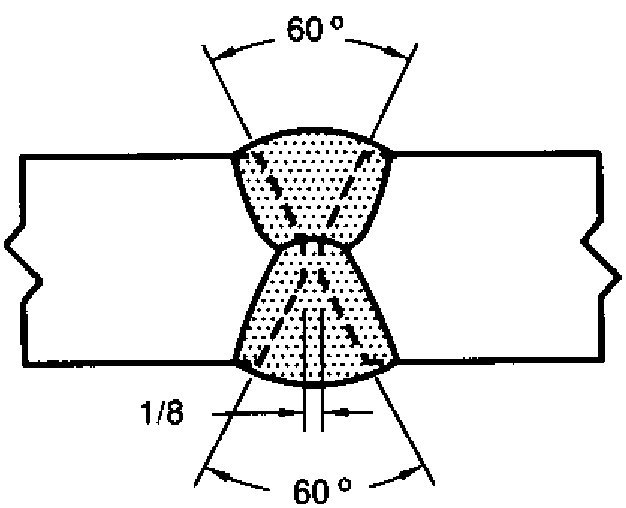


Joint Geometry with Insert in Place

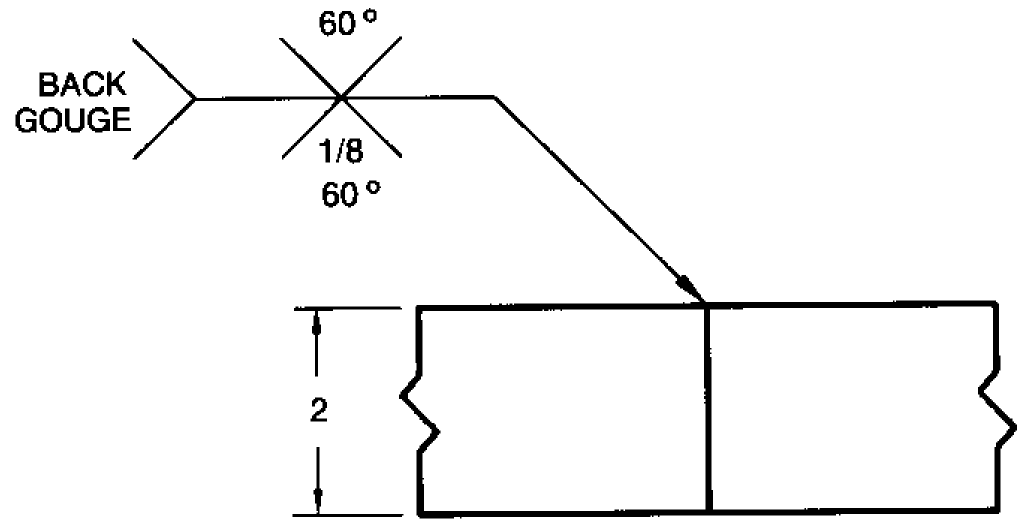


Joint with Root Pass Combined

Groove Welds with Back Gouging

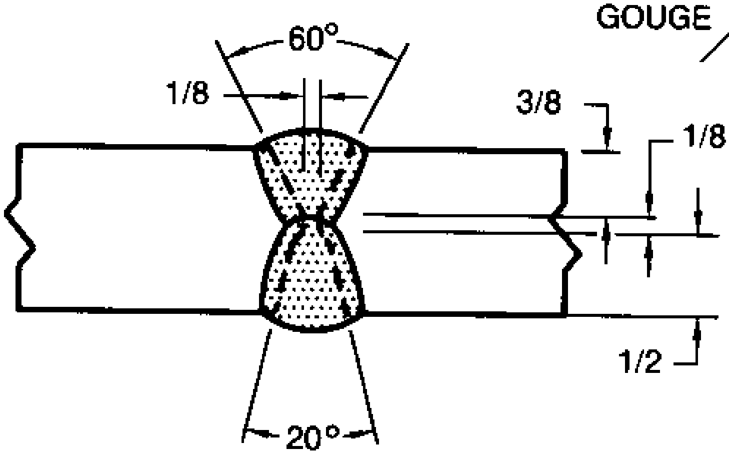


WELD CROSS SECTION



SYMBOL

Groove Welds with Back Gouging



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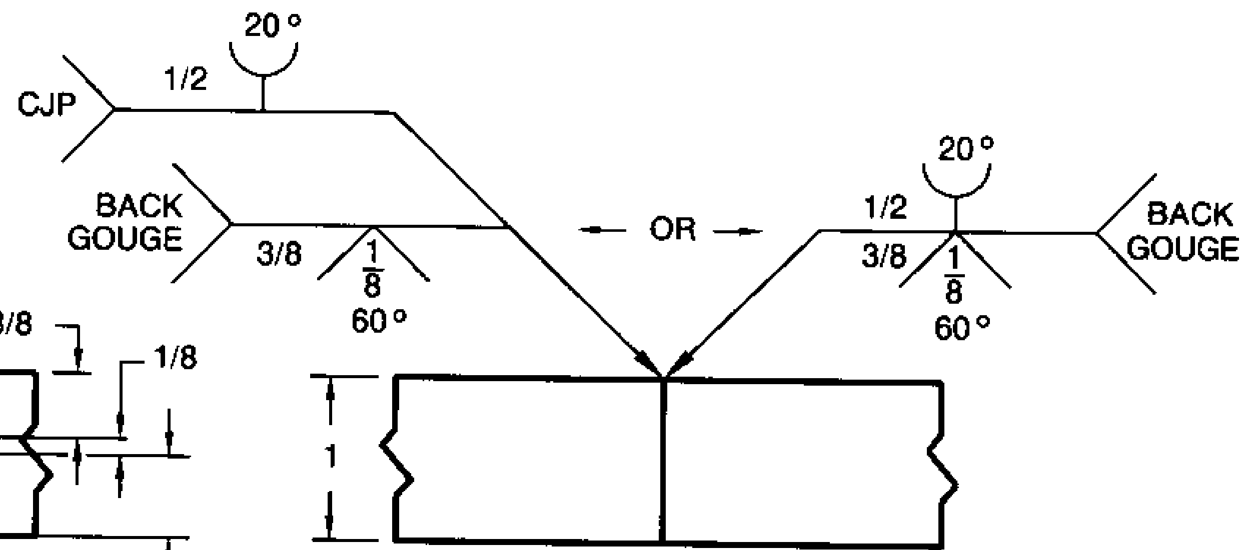
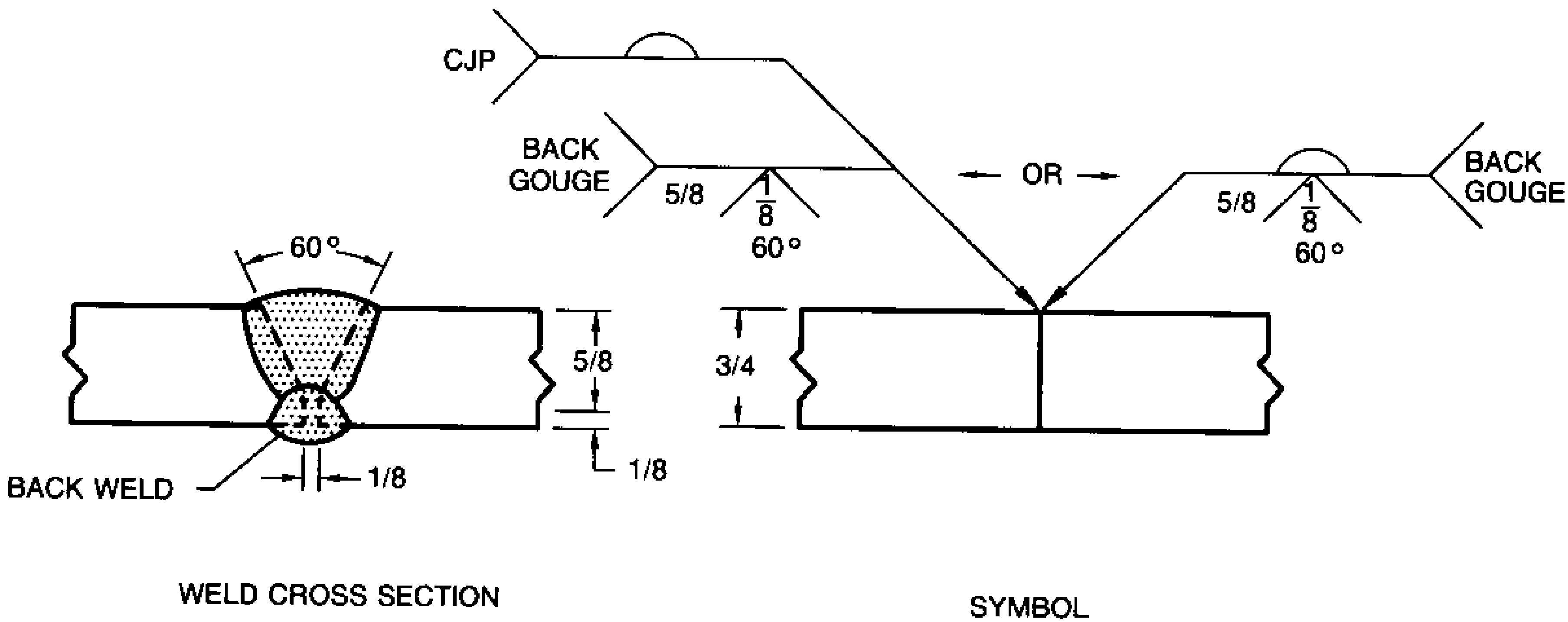
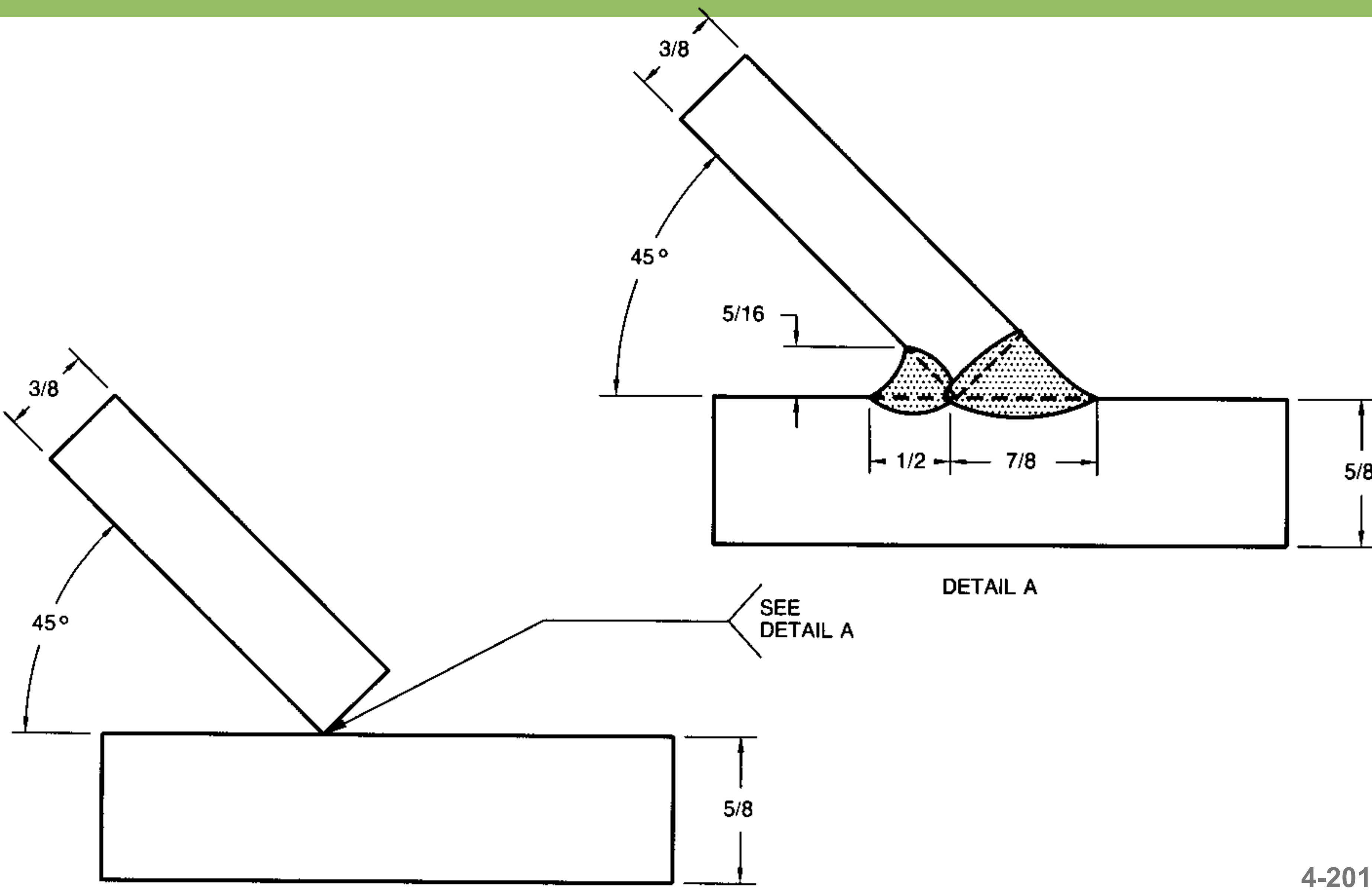


SYMBOL

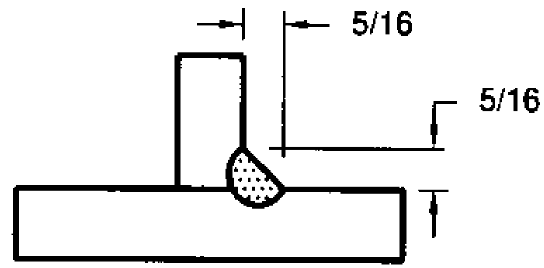
Groove Welds with Back Gouging



Skewed T-Joint



Size of Fillet Welds



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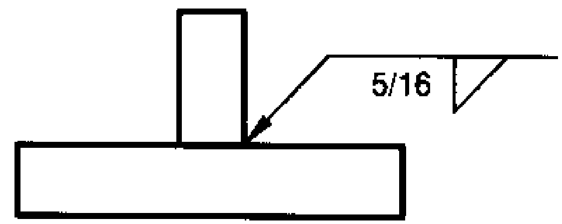
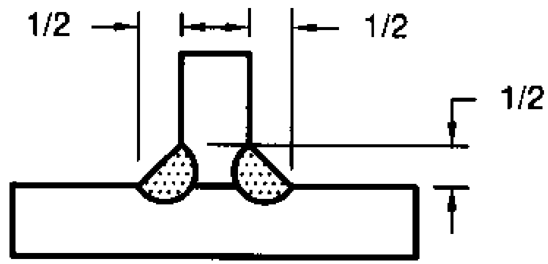


SYMBOL



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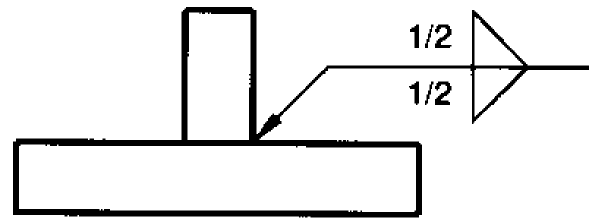
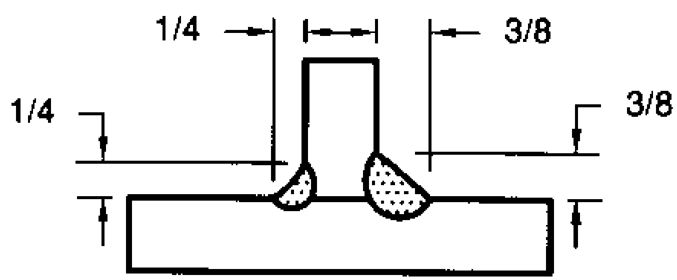


SYMBOL



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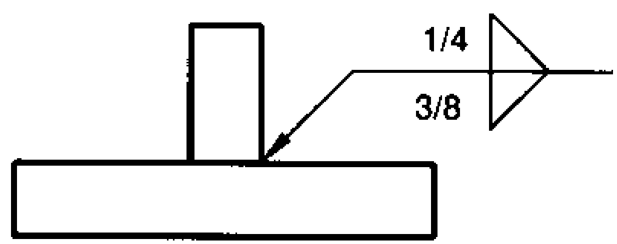
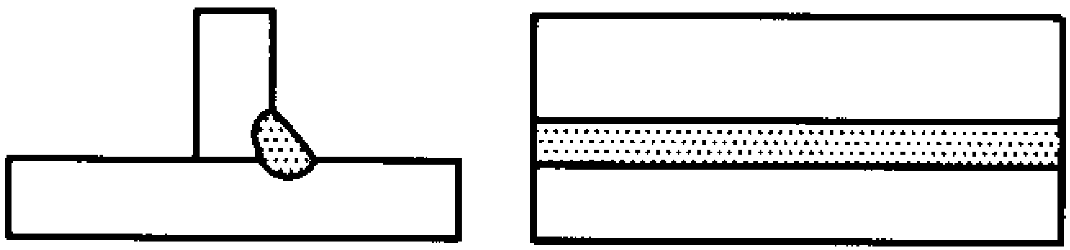


SYMBOL

Length of Fillet Welds



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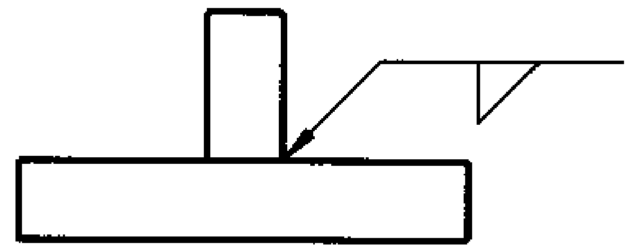
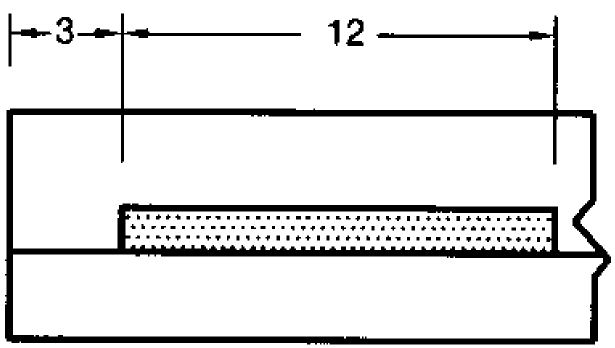
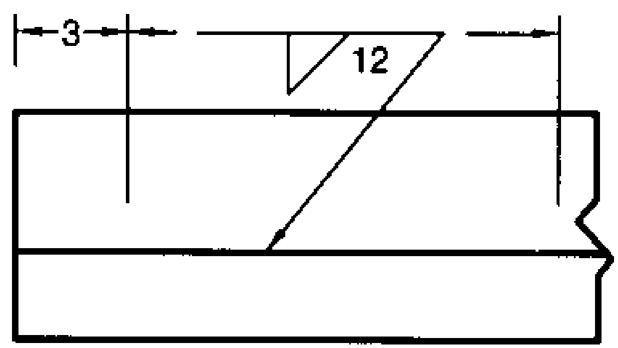


SYMBOL

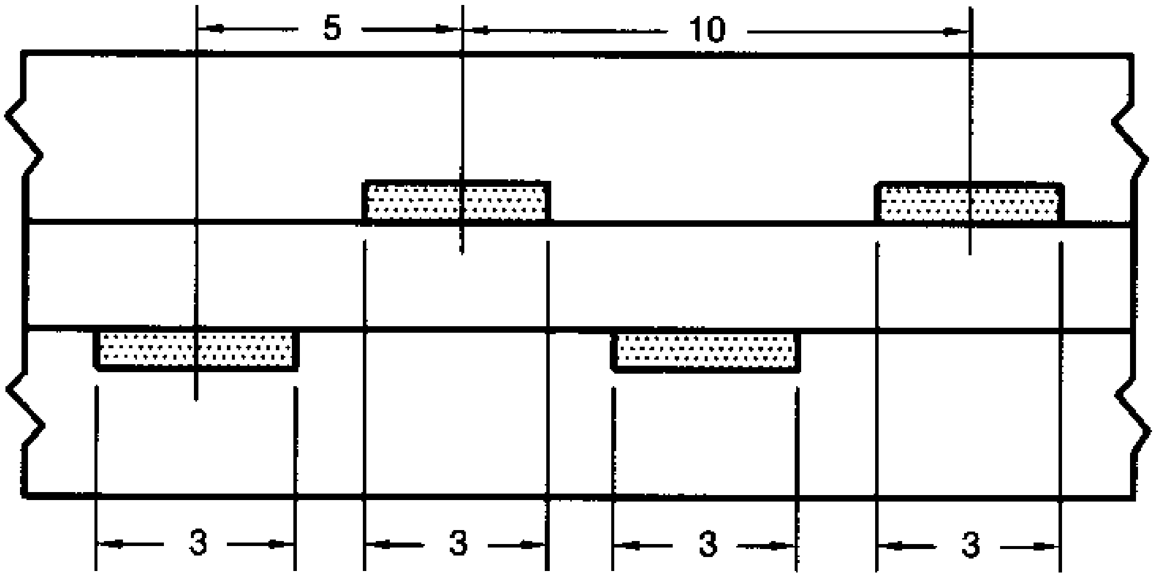


WELD

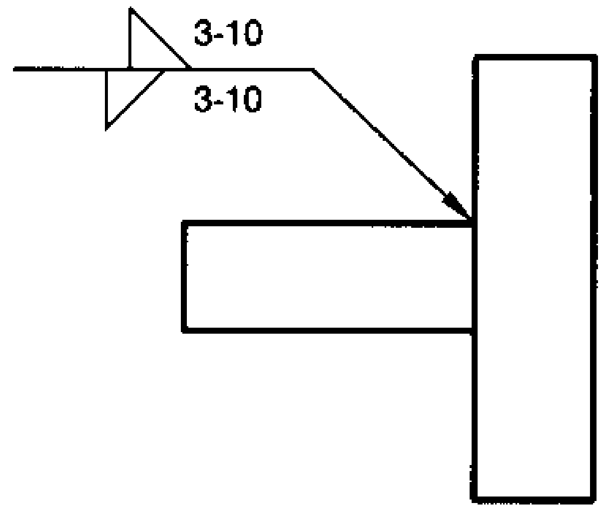


SYMBOL

Staggered Intermittent Fillet Welds

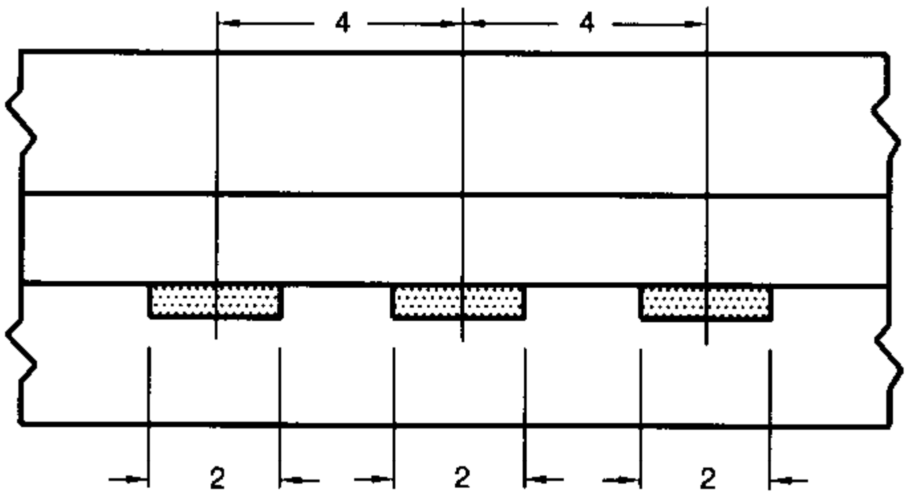


WELDS

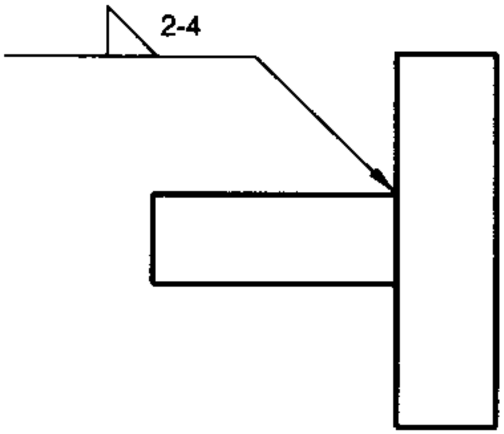


SYMBOL

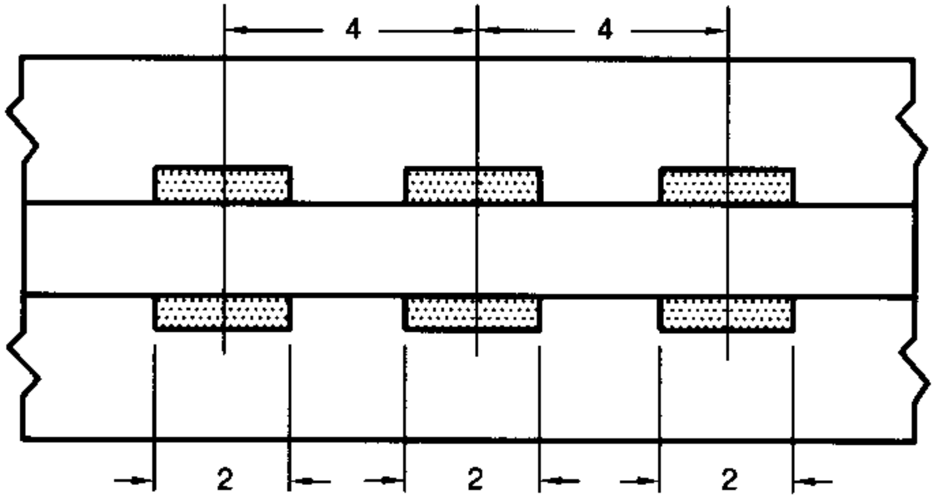
Chain Intermittent Fillet Welds



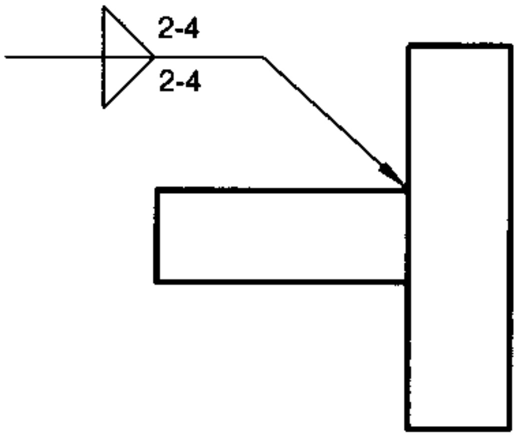
WELDS



SYMBOL

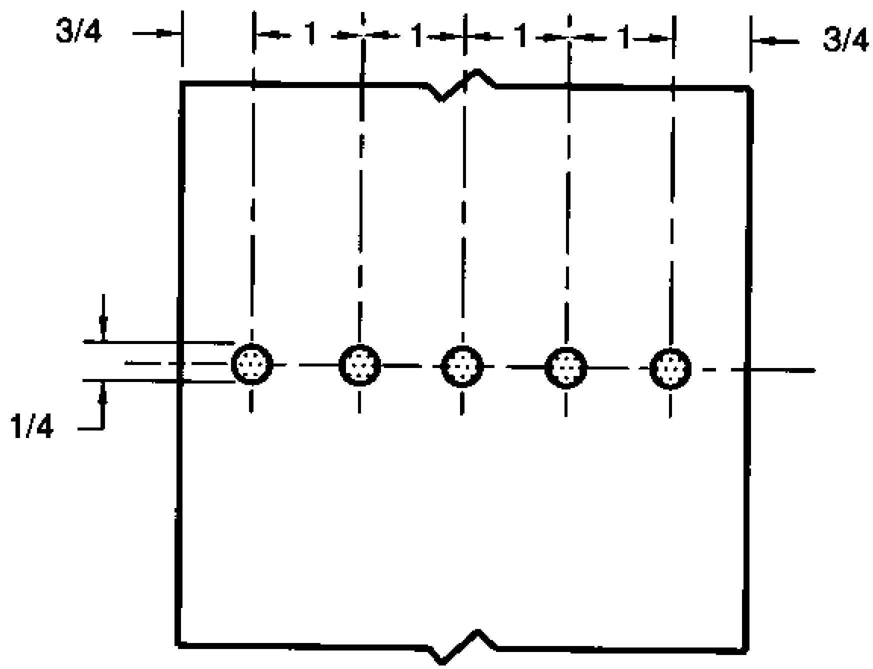


WELDS

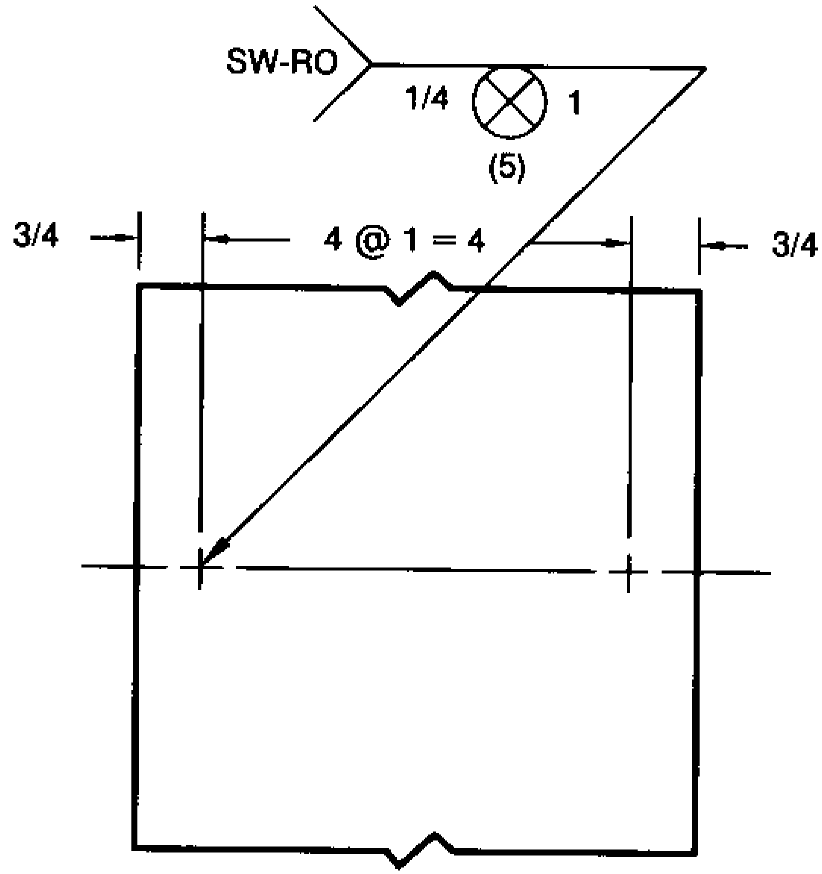


SYMBOL

Applications of Stud Weld Symbols

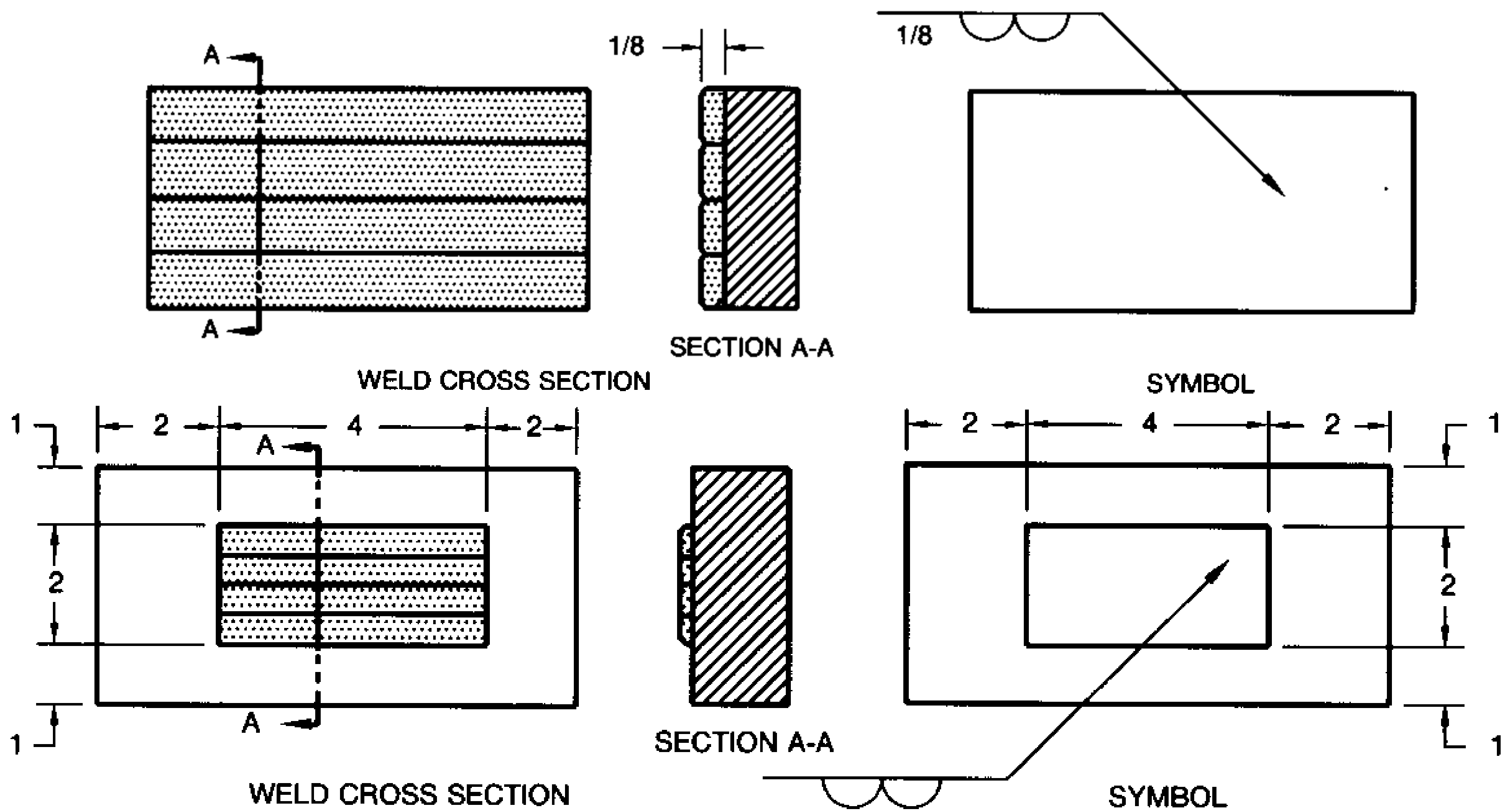


WELDS

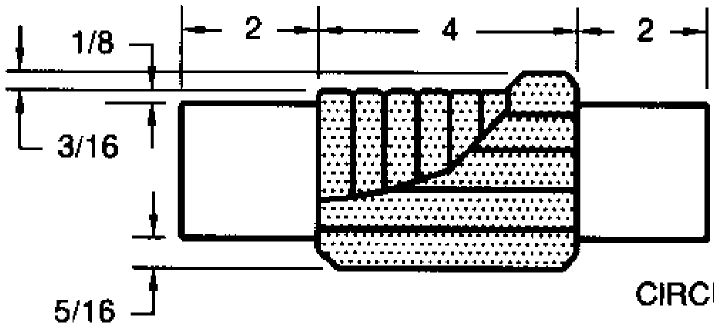


SYMBOL

Applications of Surfacing Weld Symbols

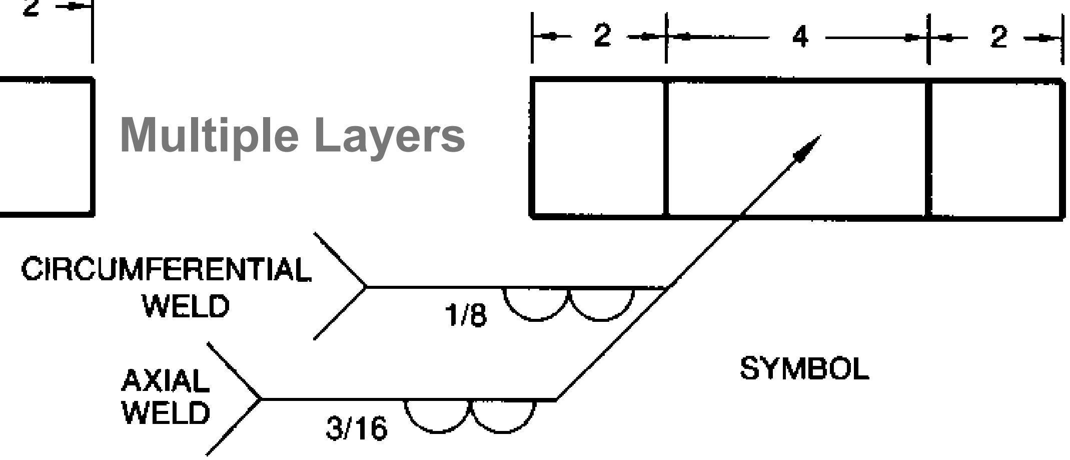


Applications of Surfacing Weld Symbols

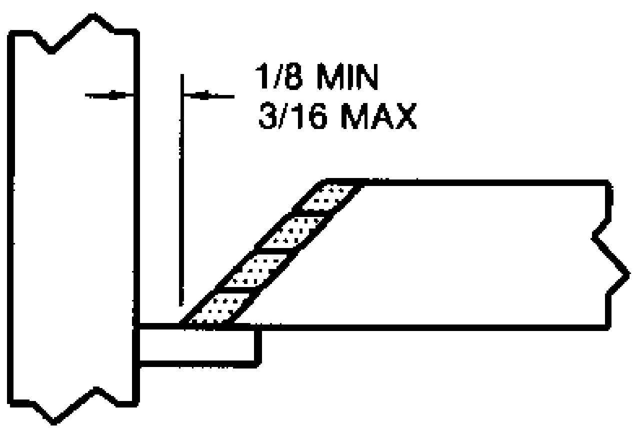


WELD CROSS SECTION

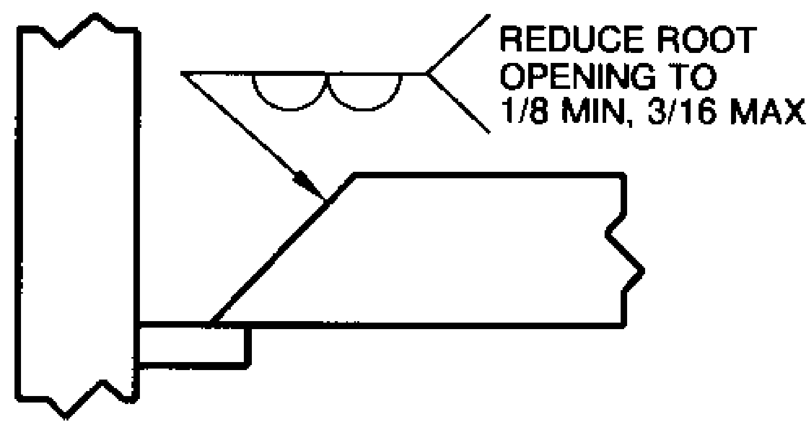
Multiple Layers



SYMBOL



WELD CROSS SECTION



SYMBOL

Mechanical Testing

Module 4F

Mechanical Testing

- There are several different sources for mechanical testing methods
  - AWS B4.0M:2000 “Standard Methods for Mechanical Testing of Welds”
  - Several ASTM standards
- There are several different sources for acceptance criteria including construction documents and qualification documents
  - ASME Section IX “Welding and Brazing Qualification”
  - AWS D1.1 “Structural Welding Code Steel”
  - API 1104 “Welding of Pipelines and Related Facilities”

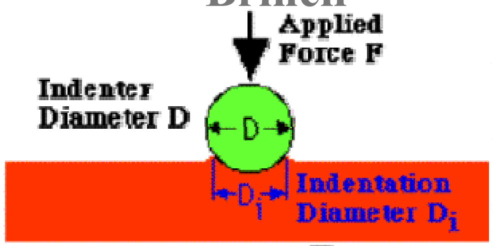
Mechanical Testing

- Testing Methods covered in this module
  - Hardness Testing
  - Tension Test
  - Bend Test
  - Fillet Weld Break Test
  - Fracture Toughness Test

Hardness Testing

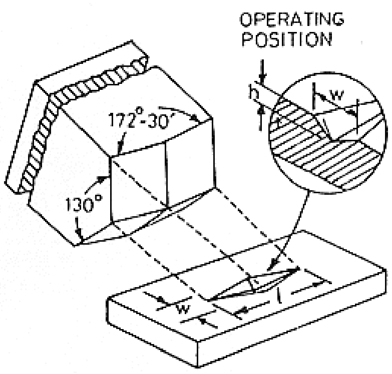
- Hardness is shorthand for strength
- Can characterize change in properties across a weld
- Several standard techniques
  - Rockwell (ASTM E-18)
  - Brinell (ASTM E 10)
  - Vickers (ASTM E92, E384)
  - Knoop (ASTM E384)
- Differences
  - Indentation load sequence
  - Indenter shape
  - Property measured
    - Indentation depth
    - Indentation area
  - Calculation of Hardness Value
- Scales related to each other

Brinell



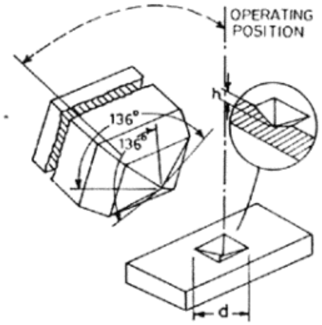
$$BHN = \frac{F}{\frac{\pi}{2} D \cdot (D - \sqrt{D^2 - D_i^2})}$$

Knoop

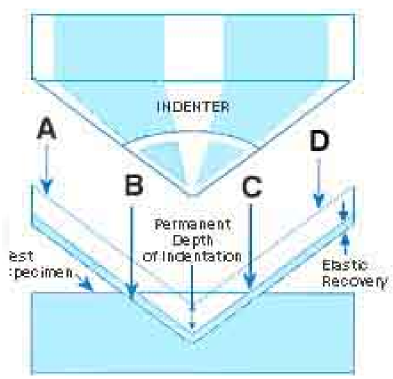


Rockwell
120° angle &
0.2mm radius

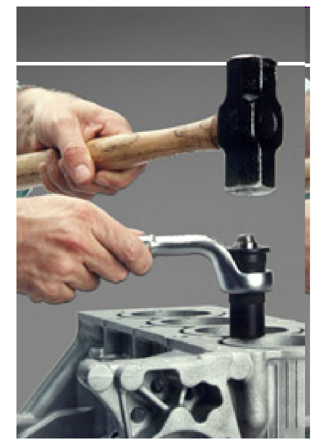
Vickers

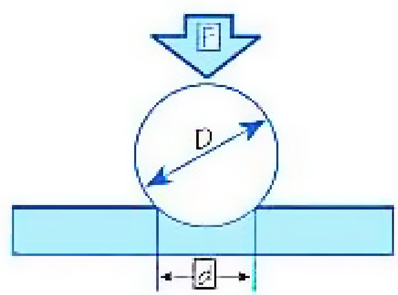


Macrohardness Test



Rockwell Test



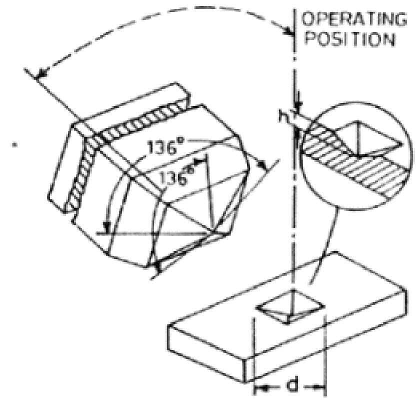


$$HB = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})}$$

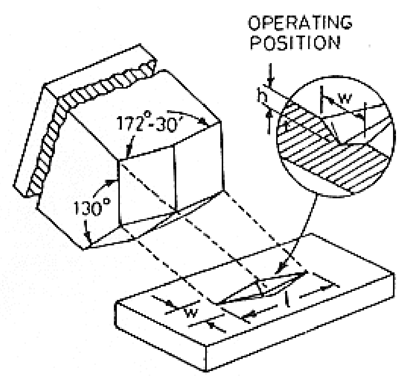
Brinell Test

Microhardness Test

Vickers



Knoop

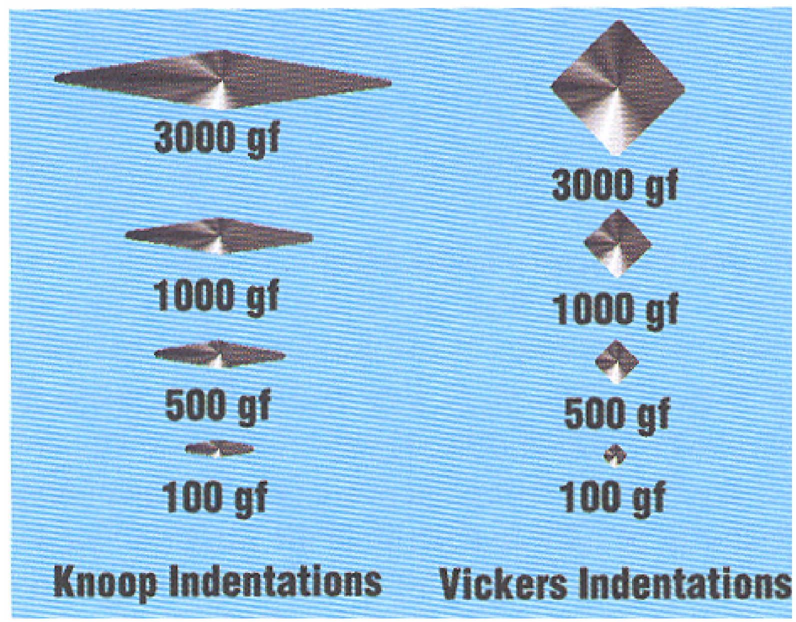


Hardness Tests, Indenters, and Shapes of Indention

Brinell		10 mm sphere of steel or tungsten carbide
Vickers		Diamond pyramid
Knoop macrohardness		Diamond pyramid
Rockwell	A, B, C	Diamond cone
	B, F, G	1/16 in. Diameter steel sphere
	E	1/8 in. Diameter steel sphere

Rockwell Indentor

Brinell Indentor



Comparison of Hardness Tests

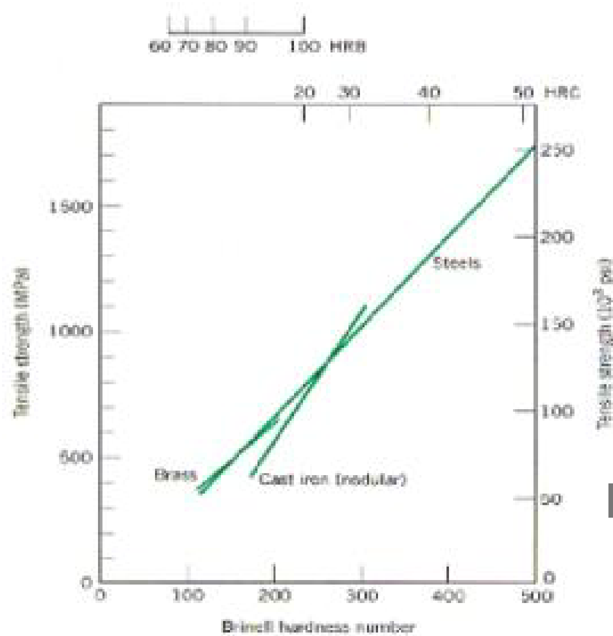
TEST	TEST METHOD	TEST FORCE RANGE	INDENTER TYPES	ASTM TEST METHOD	MEASURE METHOD
Rockwell	Regular	60, 100, 150 kgs	Conical Diamond & Small Ball	E 18	Depth
	Superficial	15, 30, 45 kgs	Conical Diamond & Small Ball	E 18	Depth
	Light Load	3, 5, 7 kgs	Truncated Cone Diamond	N/A	Depth
	Micro	500, 100 grams	Small Truncated Cone Diamond	N/A	Depth
	Macro	500 to 3000 kgs	5, 10 mm Ball	E 103	Depth
Micro-Hardness	Vickers	5 to 2000 grams	136° Pyramid Diamond	E 384	Area
	Knoop	5 to 2000 grams	1300 x 1720° Diamond	E 384	Area
	Rockwell Type	500, 3000 grams	Truncated Cone Diamond	N/A	Depth
	Dynamic	.01 to 200 grams	Triangular Diamond	N/A	Depth
Brinell	Optical	500 to 3000 kgs	5mm, 10 mm Ball	E 10	Area
	Depth	500 to 3000 kgs	5mm, 10 mm Ball	E 103	Depth
Shore	Regular	822 (A), 4550 (D) grams	35° Cone (A) 30° Cone (D)	D 2240	Depth
	Micro	257 (A), 1135 (D) grams	35° Cone (A) 30° Cone (D)	N/A	Depth
IRHD	Regular	597 grams	2.5 mm Ball	D 1415	Depth
	Micro	15.7 grams	.395 mm Ball	D 1415	Depth

Microhardness testing often used to characterize changes in strength across a weld and Heat Affected Zone

Hardness Relationship to Mechanical Properties

- Hardness can be used to estimate material strength
  - Estimated tensile strength of steel
    - 510 * HB, HB<175
    - 490 * HB, HB>175
  - Estimated yield strength of steel
    - 0.33* hardness
    - (Vickers * 10/3 = Tensile yield)

Hardness & Tensile Strength



$$\sigma_{TS} = 500 \times HB$$

HB = Brinell Hardness

Hardness Scale Conversion

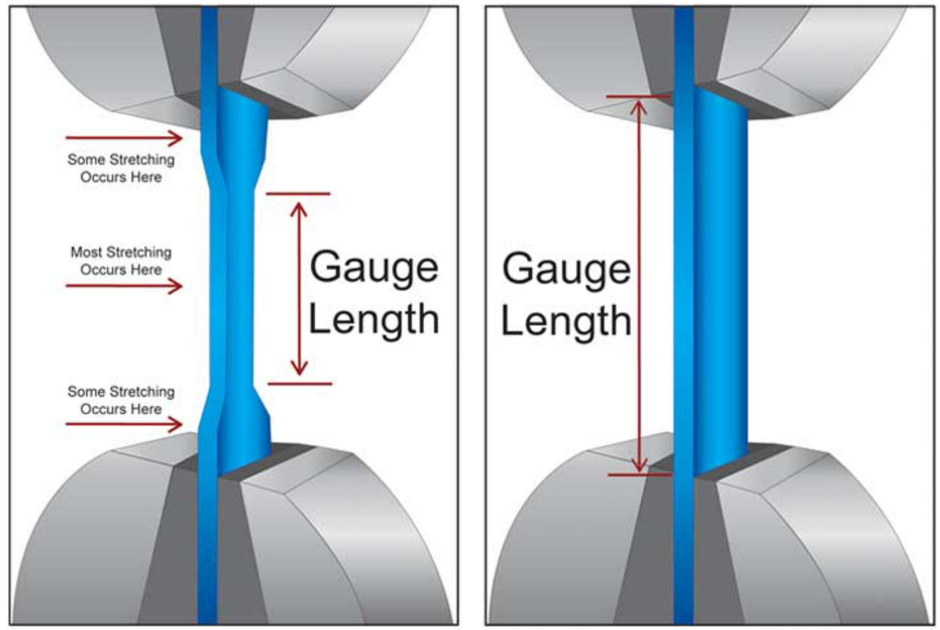
Rockwell C	Brinell	Vickers	Tensile ksi
60	654	697	
55	560	595	288
50	481	513	245
45	421	446	212
40	390	412	191
35	327	345	163
30	286	302	142
25	253	266	125

Tension Test

- Summary of Method
  - Tension testing of welded joints is done by means of a calibrated testing machine and devices
  - The test sample is pulled in tension until the sample fails
- Significance
  - Tension test provides information on properties of welded joints: load bearing capacities; joint design; and ductility

Tension Test – Summary of Method

Test coupon in the loading grips

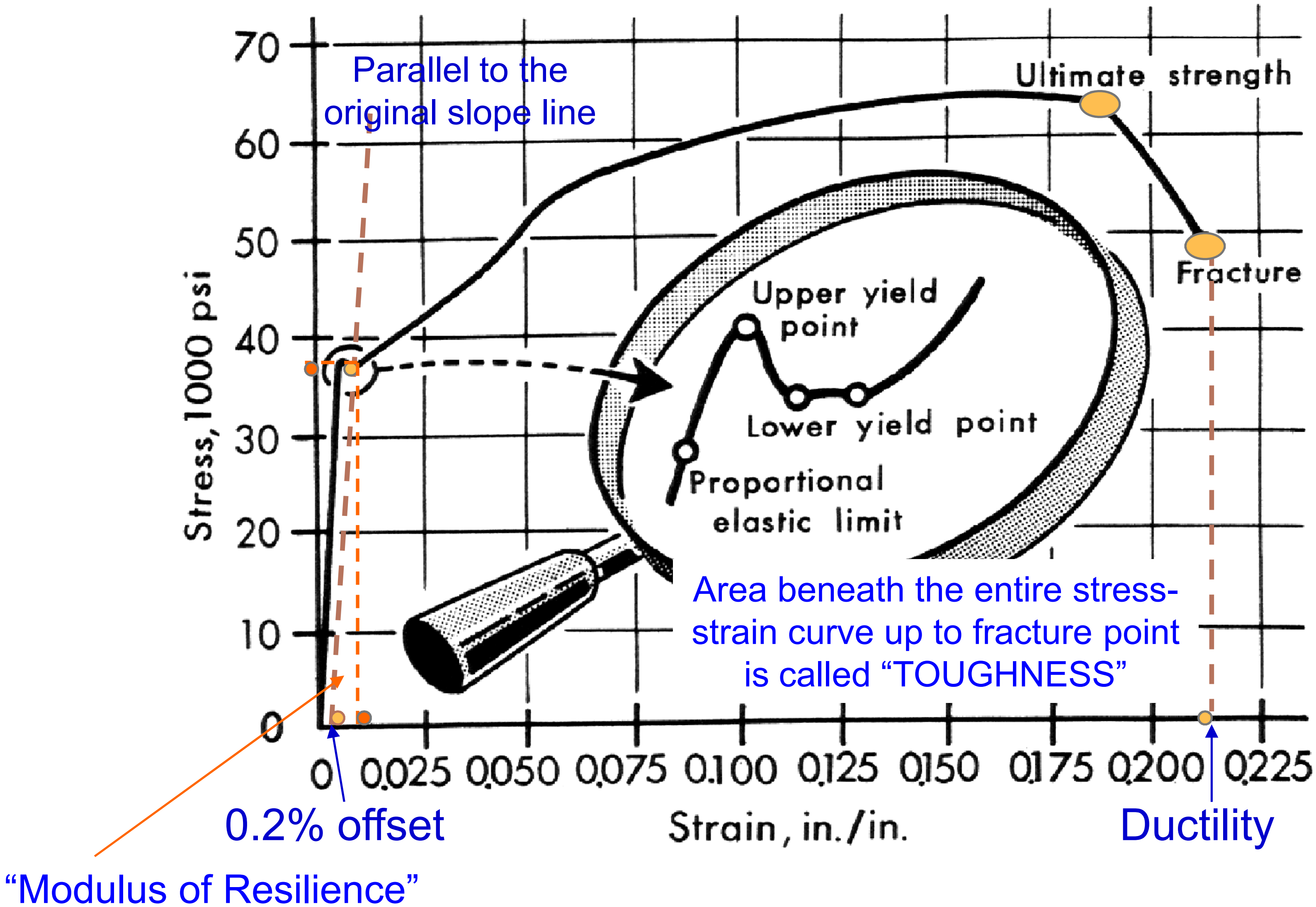


Initial Gauge Length

$$Stress = \frac{Load}{Initial..Cross - Sectional..Area}$$

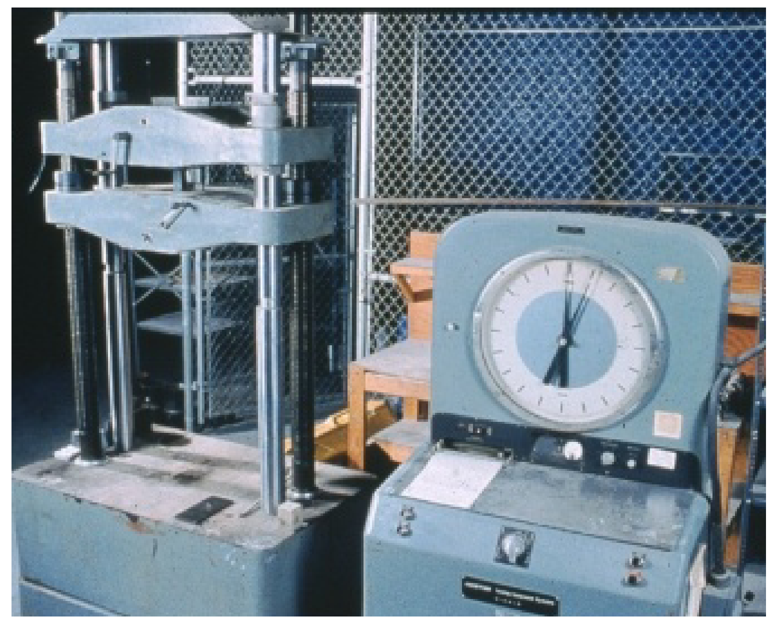
$$Strain = \frac{Elongation}{Initial..Gauge..Length}$$

Stress-Strain Curve



Tension Test Apparatus

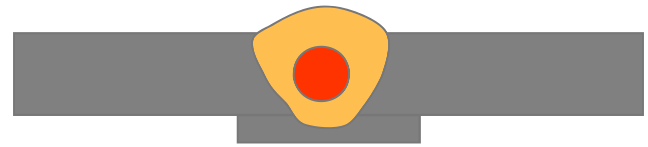
Modern Loading System - Computer Controlled

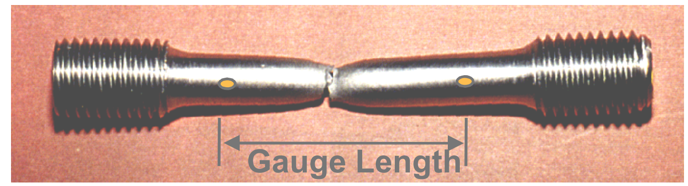


Conventional Loading System – for Tensile Strength Only

Tensile Test - Specimens

- All Weld Metal Tensile Test
  - Determine weld metal ultimate tensile strength, yield strength, elongation and reduction in area
- Reduced Section Tension Test (RST)
  - Determine ultimate tensile strength only
- Specimens shall be tensile tested in the as-welded condition unless the procedure qualification requires a PWHT





Tensile Test - Procedure

- Welding Procedure Qualification
  - Tension test specimen shall be ruptured under tensile load
  - Tensile strength shall be computed by dividing the ultimate total load by the least cross-sectional area of the specimen as calculated from actual measurements made before the load is applied

Round Tension Specimen

Ultimate Tensile Strength $$UTS = \frac{Maximum\ ..Load}{\left(\frac{\pi D^2}{4}\right)}$$

Yield Strength at Specified Offset $$YS = \frac{Load\ ..@\ ..Offset}{\left(\frac{\pi D^2}{4}\right)}$$

Percent Elongation $$\varepsilon_f = \frac{Final\ ..GaugeL\ ..Length - Original\ ..Gauge\ ..Length}{Original\ ..Gauge\ ..Length}$$

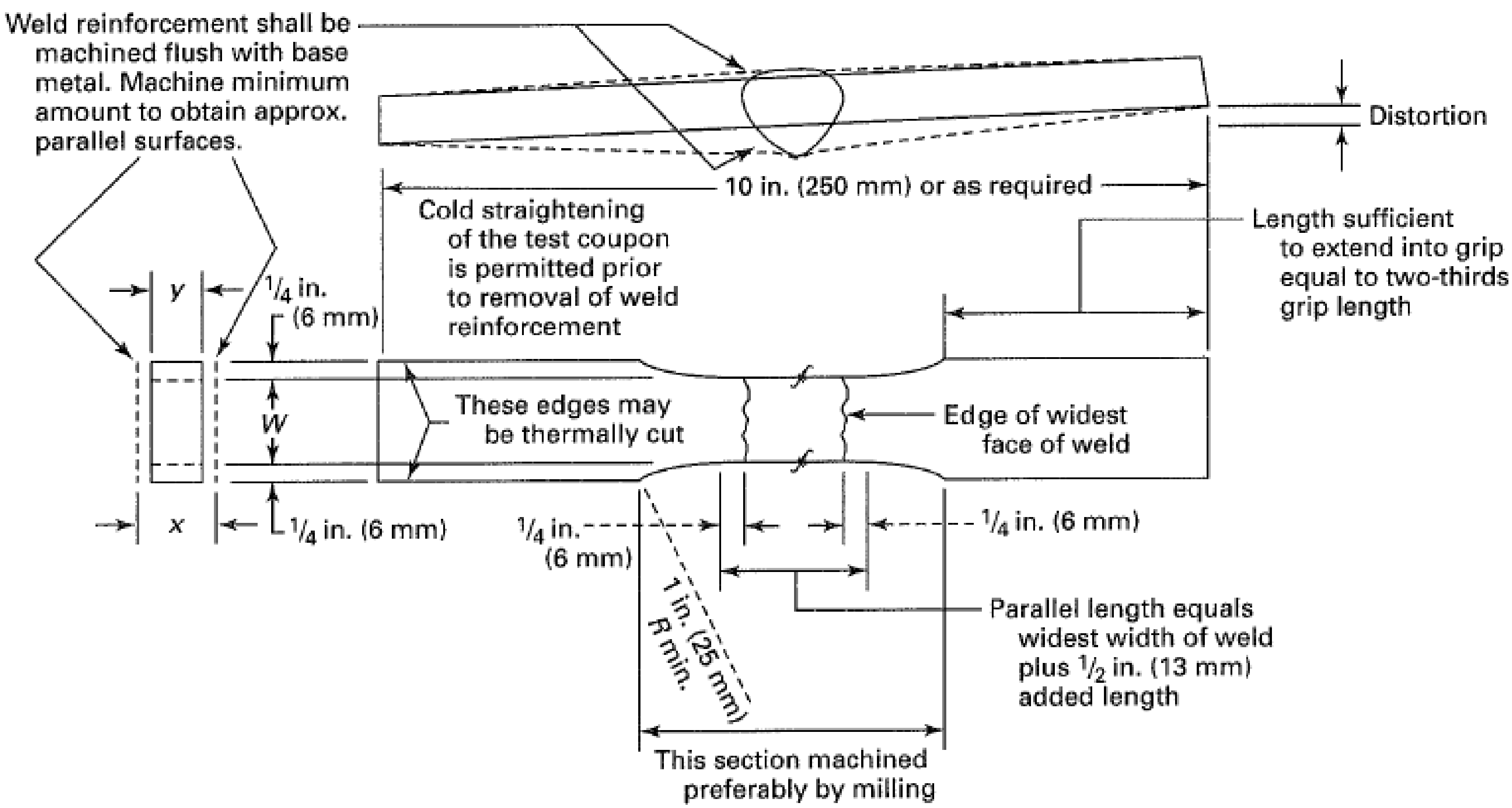
Reduced Section Tension Specimen

Ultimate Tensile Strength $$UTS = \frac{Maximum\ ..Load}{Original\ ..Cross - Section\ ..Area}$$

ASME Section IX – QW-150 Tension Test

- QW-151.1, Reduced Section – Plate

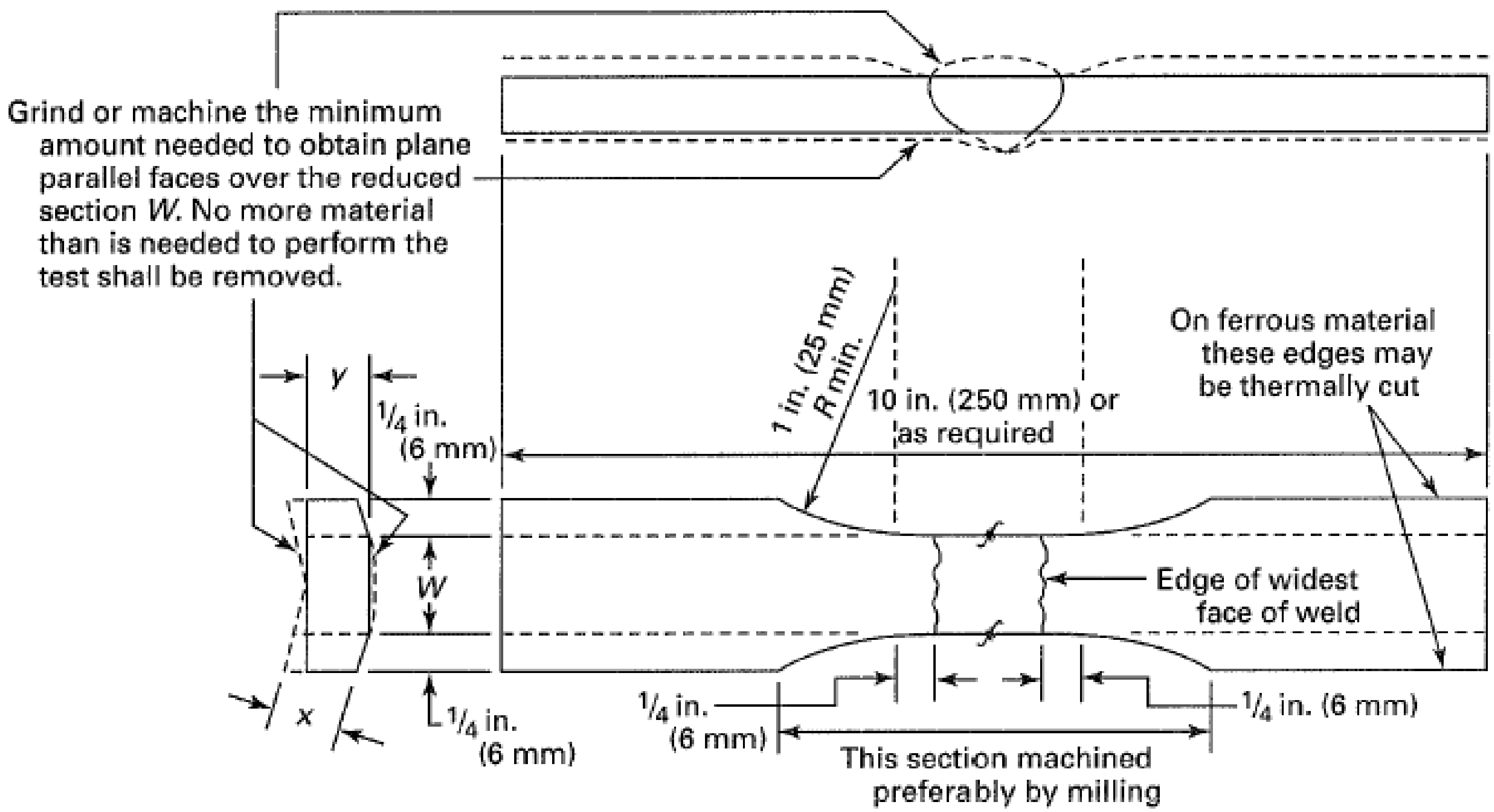
QW-462.1(a) TENSION — REDUCED SECTION — PLATE



ASME Section IX – QW-150 Tension Test

- QW-151.2, Reduced Section – Pipe
  - For pipe diameters greater than 3 in.

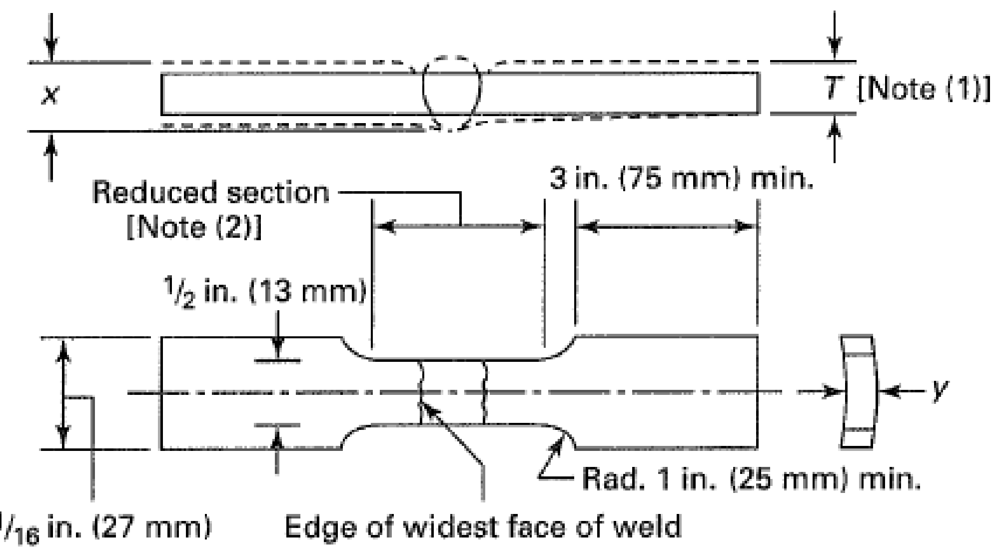
QW-462.1(b) TENSION — REDUCED SECTION — PIPE



ASME Section IX – QW-150 Tension Test

- QW-151.2, Reduced Section – Pipe
  - For pipe diameters less than or equal to 3 in.

QW-462.1(c) TENSION — REDUCED SECTION ALTERNATE FOR PIPE

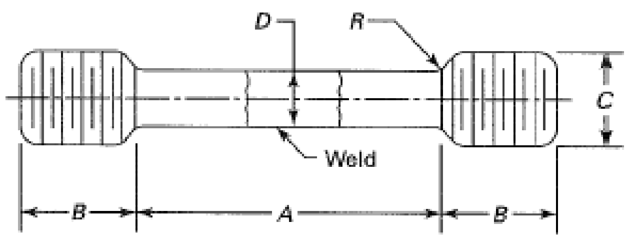


NOTES:
(1) The weld reinforcement shall be ground or machined so that the weld thickness does not exceed the base metal thickness *T*. Machine minimum amount to obtain approximately parallel surfaces.
(2) The reduced section shall not be less than the width of the weld plus 2*y*.

ASME Section IX – QW-150 Tension Test

- QW-151.3, Turned Specimen

QW-462.1(d) TENSION — REDUCED SECTION — TURNED SPECIMENS



	Standard Dimensions, in. (mm)			
	(a) 0.505 Specimen	(b) 0.353 Specimen	(c) 0.252 Specimen	(d) 0.188 Specimen
A—Length of reduced section	Note (1)	Note (1)	Note (1)	Note (1)
D—Diameter	0.500 ± 0.010 (12.7 ± 0.25)	0.350 ± 0.007 (8.89 ± 0.18)	0.250 ± 0.005 (6.35 ± 0.13)	0.188 ± 0.003 (4.78 ± 0.08)
R—Radius of fillet	3/8 (10) min.	1/4 (6) min.	3/16 (5) min.	1/8 (3) min.
B—Length of end section	1 3/8 (35) approx.	1 1/8 (29) approx.	7/8 (22) approx.	1/2 (13) approx.
C—Diameter of end section	3/4 (19)	1/2 (13)	3/8 (10)	1/4 (6)

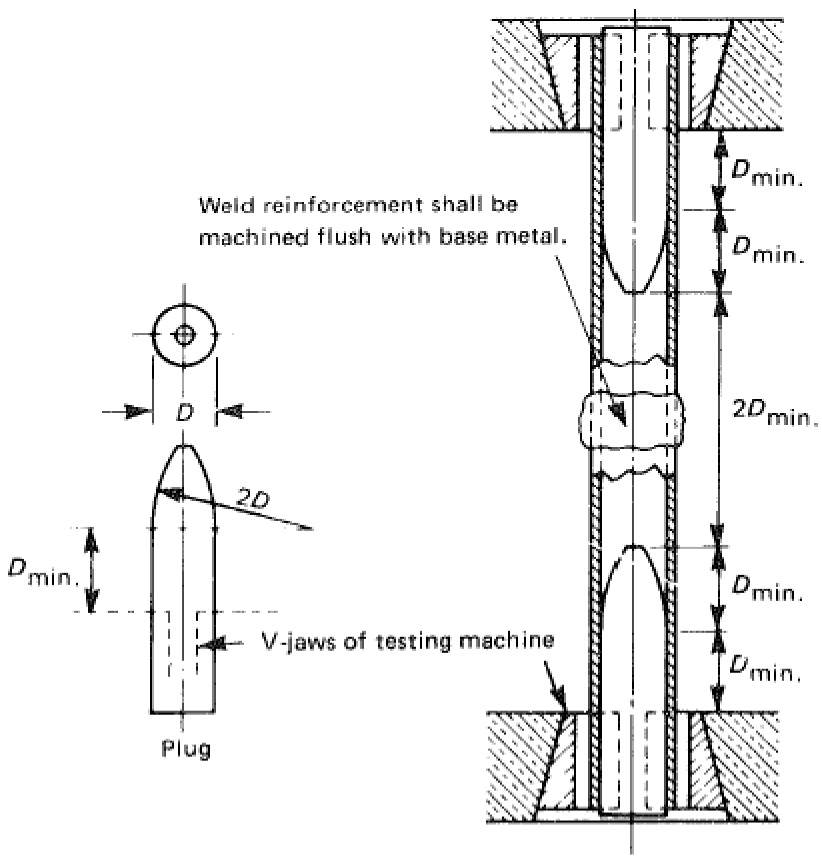
GENERAL NOTES:
(a) Use maximum diameter specimen (a), (b), (c), or (d) that can be cut from the section.
(b) Weld should be in center of reduced section.
(c) Where only a single coupon is required, the center of the specimen should be midway between the surfaces.
(d) The ends may be of any shape to fit the holders of the testing machine in such a way that the load is applied axially.

NOTE:
(1) Reduced section *A* should not be less than width of weld plus 2*D*.

ASME Section IX – QW-150 Tension Test

- QW-151.4, Full-Section Specimens for Pipe
  - For pipe diameters less than or equal to 3 in.

QW-462.1(e) TENSION — FULL SECTION — SMALL DIAMETER PIPE



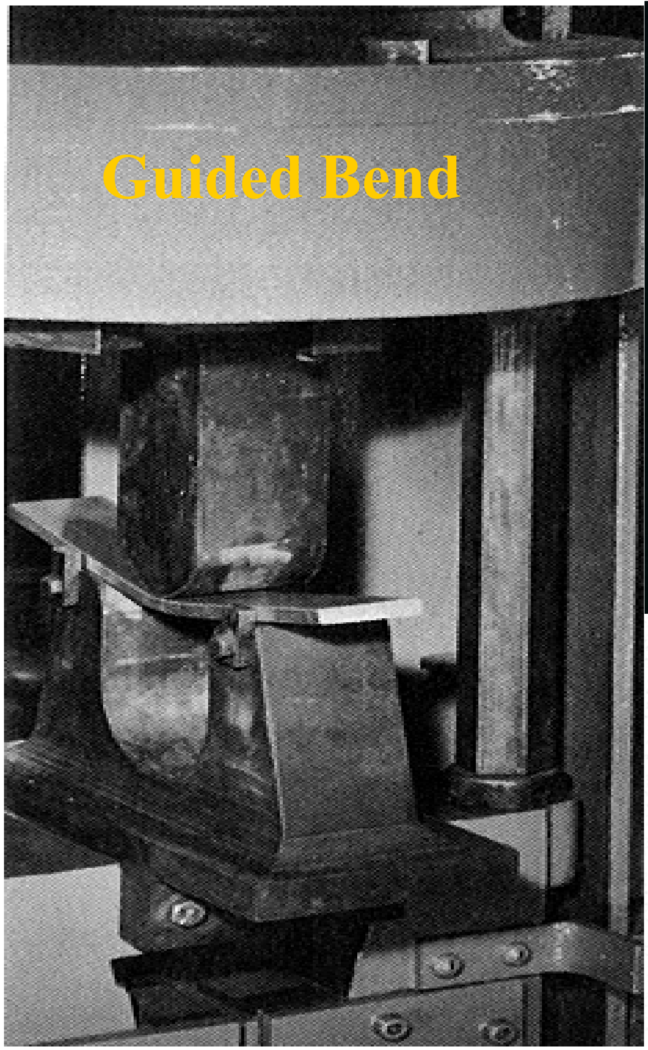
Tensile Test – Acceptance Criterion

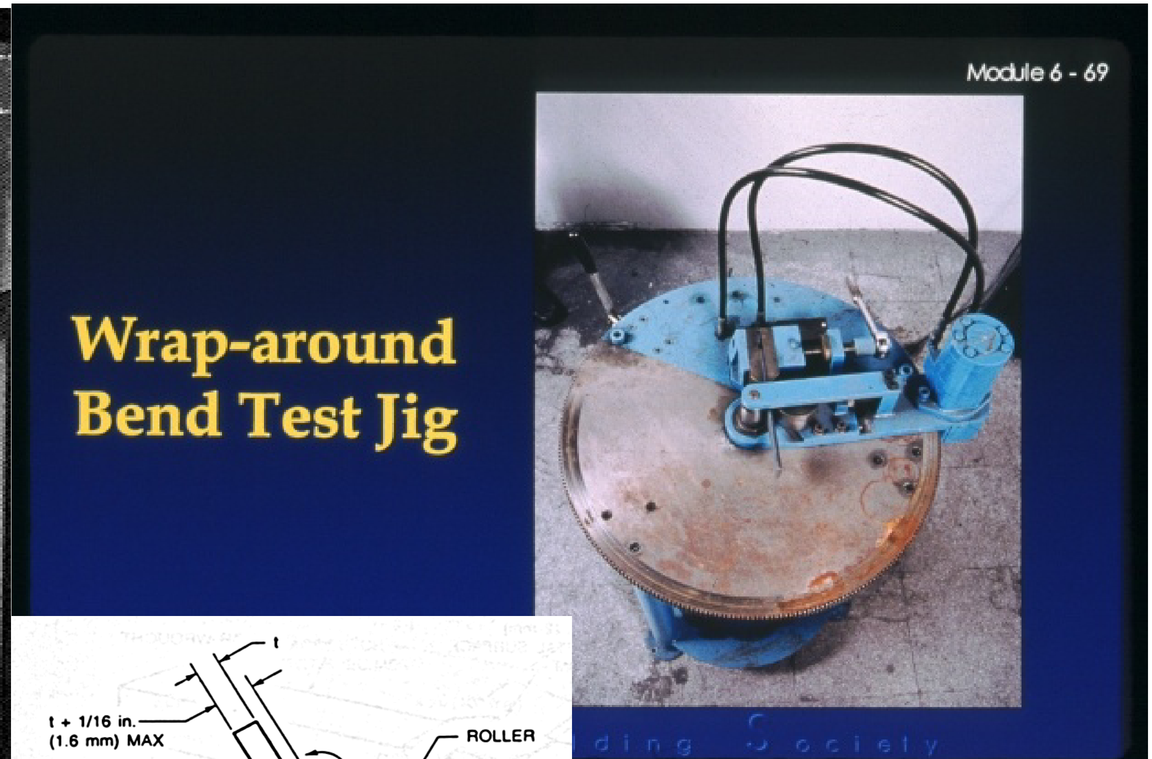
- Reduced Section Tension per AWS D1.1
  - 4.8.3.5 Acceptance Criteria for Reduced-Section Tension Test
    - The tensile strength shall be no less than the minimum of the specified tensile range of the base metal used
- Reduced Section Tension per ASME Section IX
  - QW-153 Acceptance Criteria – Tension Test
    - To pass the tension test the specimen shall have a tensile strength that is
      - not less than the minimum specified tensile strength of the base metal, or
      - not less than the minimum specified tensile strength of the weaker of the two materials if different strength materials are welded, or
      - not less than the minimum specified tensile strength of the weld metal when a weld metal having lower room temperature strength than the base metal is allowed, or
      - if specimen breaks in base metal outside the weld or fusion line, the test shall be accepted, provided the strength is not more than 5% below the minimum specified tensile strength of the base metal

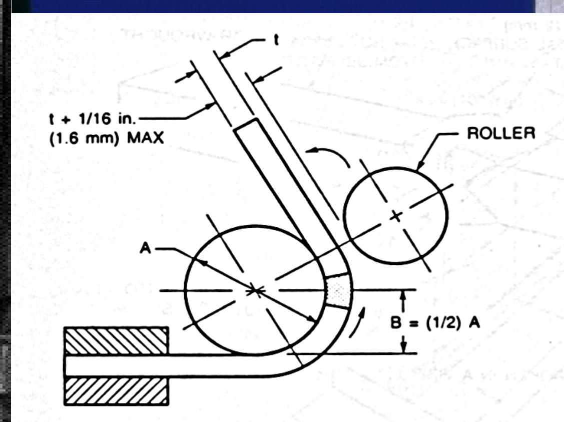
Guided Bend Test

- Summary of Method
  - The specimens are guided in the bending process by a test fixture that employs a mandrel with wraparound roller or end supports with plunger
  - The maximum strain on the tension surface is controlled by the thickness of the specimen and the radius of the mandrel or plunger
- Significance
  - The ductility of a welded joint

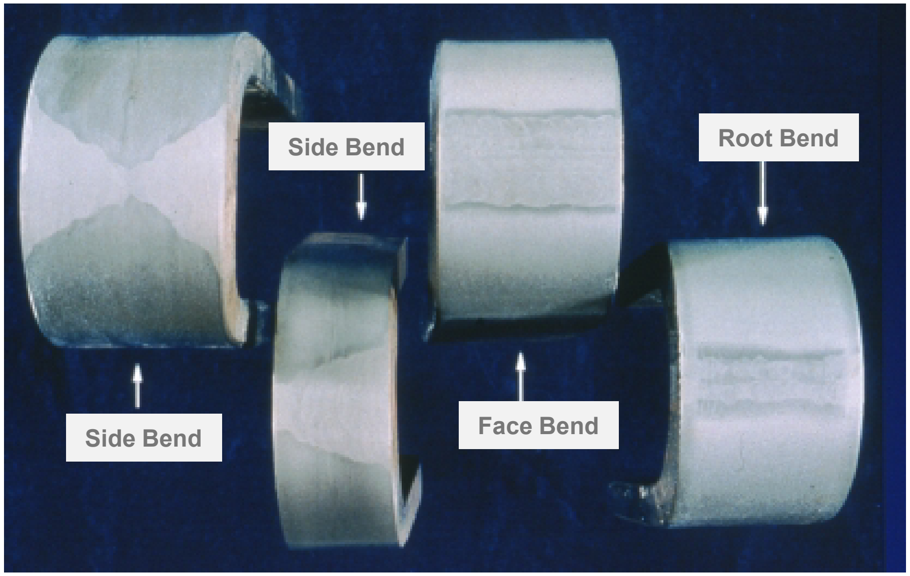
Bend Test Apparatus



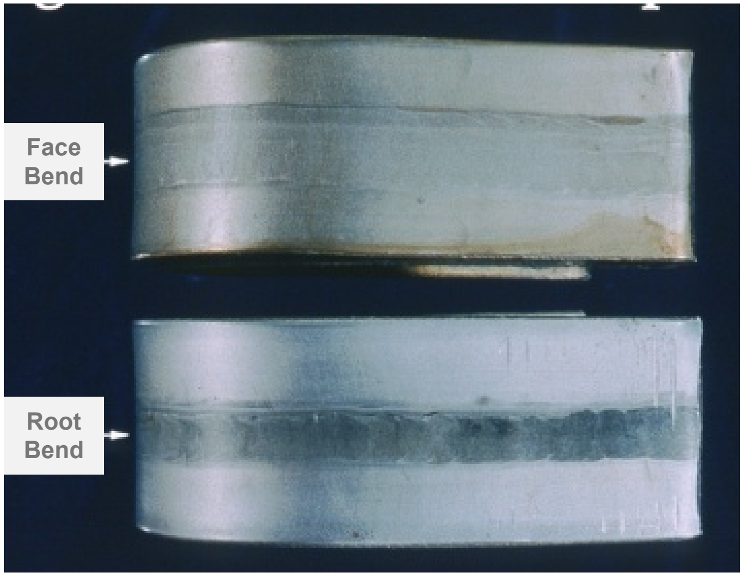




Guided Bend Test Specimens



Transverse Bend Test Specimens



Longitudinal Bend Test Specimens

Guided Bend Test Procedure

- Specimens shall be bent in jigs
- The weld and HAZ shall be within the curved portion of the specimen if not the specimen shall be discarded
- Unless otherwise specified, the specimen shall be tested at ambient temperature and deformation shall occur in a time period between 15 seconds and 2 minutes
- Appropriate surface of the specimen, according to its type, shall be bent such that it is placed in tension
- Specimen shall be bent around the correct size mandrel (plunger) until the specimen is forced into the die until a 1/8” wire cannot be inserted between the specimen and die, or the specimen is bottom ejected if the roller type jig is used
- When specimens wider than 1-1/2” are tested, mandrel must be at least 1/4” wider than specimen

ASME Section IX – QW-160 Guided Bend Test

- QW-161.1, Transverse Side Bend

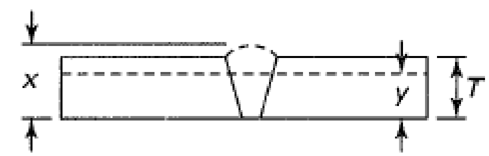
QW-462.2 SIDE BEND

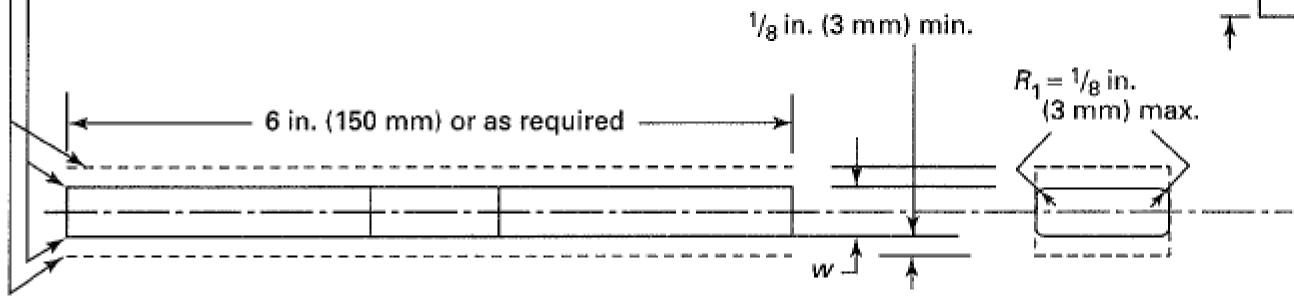
(1a) For procedure qualification of materials other than P-No. 1 in QW-422, if the surfaces of the side bend test specimens are gas cut, removal by machining or grinding of not less than 1/8 in. (3 mm) from the surface shall be required.

(1b) Such removal is not required for P-No. 1 materials, but any resulting roughness shall be dressed by machining or grinding.

(2) For performance qualification of all materials in QW-422, if the surfaces of side bend tests are gas cut, any resulting roughness shall be dressed by machining or grinding.

T, in. (mm)	*y*, in. (mm)	*w*, in. (mm)	
		P-No. 23, F-No. 23, or P-No. 35	All other metals
3/8 to < 1 1/2 (10 to < 38)	*T* [Note (1)]	1/8 (3)	3/8 (10)
≥ 1 1/2 (≥ 38)	Notes (1) and (2)	1/8 (3)	3/8 (10)

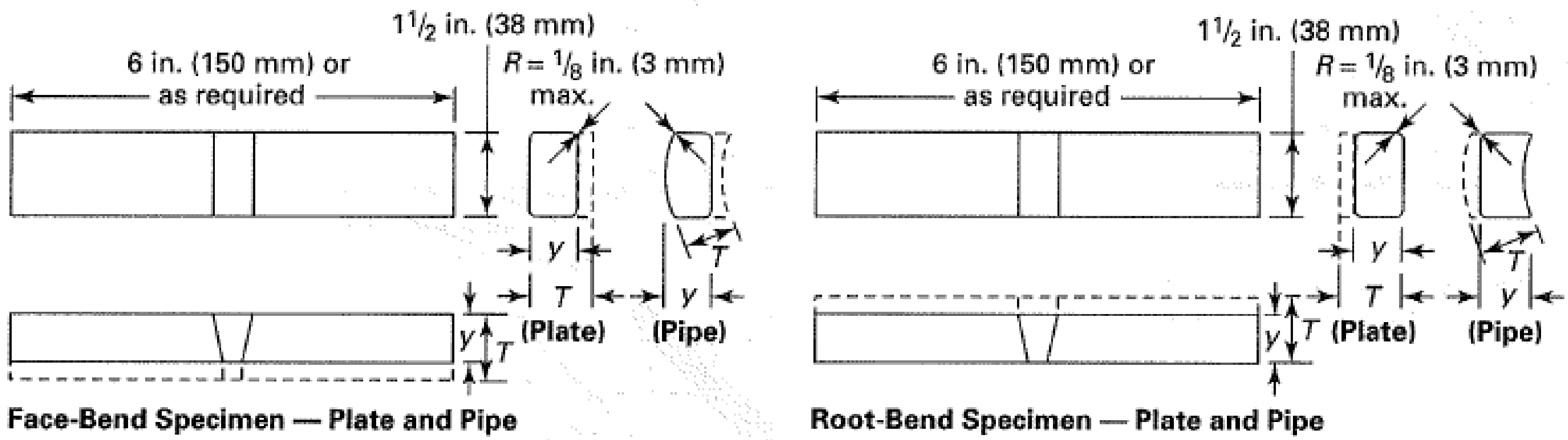




ASME Section IX – QW-160 Guided Bend Test

- QW-161.2 and 161.3, Transverse Face or Root Bend

QW-462.3(a) FACE AND ROOT BENDS — TRANSVERSE

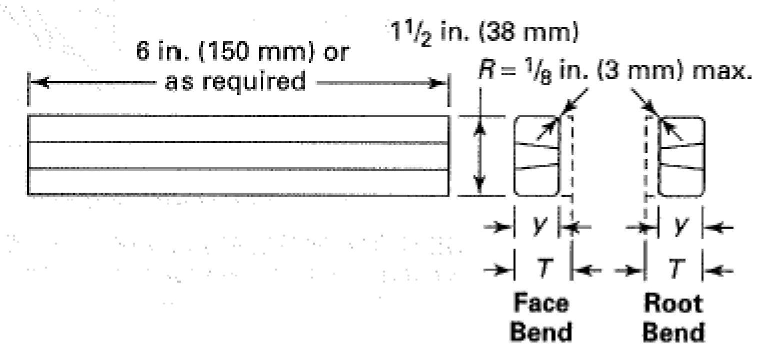


T, in. (mm)	Y, in. (mm)	
	P-No. 23, F-No. 23, or P-No. 35	All Other Metals
$\frac{1}{16} < \frac{1}{8}$ (1.5 < 3)	T	T
$\frac{1}{8}$–$\frac{3}{8}$ (3–10)	$\frac{1}{8}$ (3)	T
$>\frac{3}{8}$ (10)	$\frac{1}{8}$ (3)	$\frac{3}{8}$ (10)

ASME Section IX – QW-160 Guided Bend Test

- QW-161.6 and 161.7, Longitudinal Face or Root Bend
  - Used to test materials with markedly different bending properties
    - Largely different properties between different base materials
    - Largely different properties between the weld metal and base material

QW-462.3(b) FACE AND ROOT BENDS — LONGITUDINAL

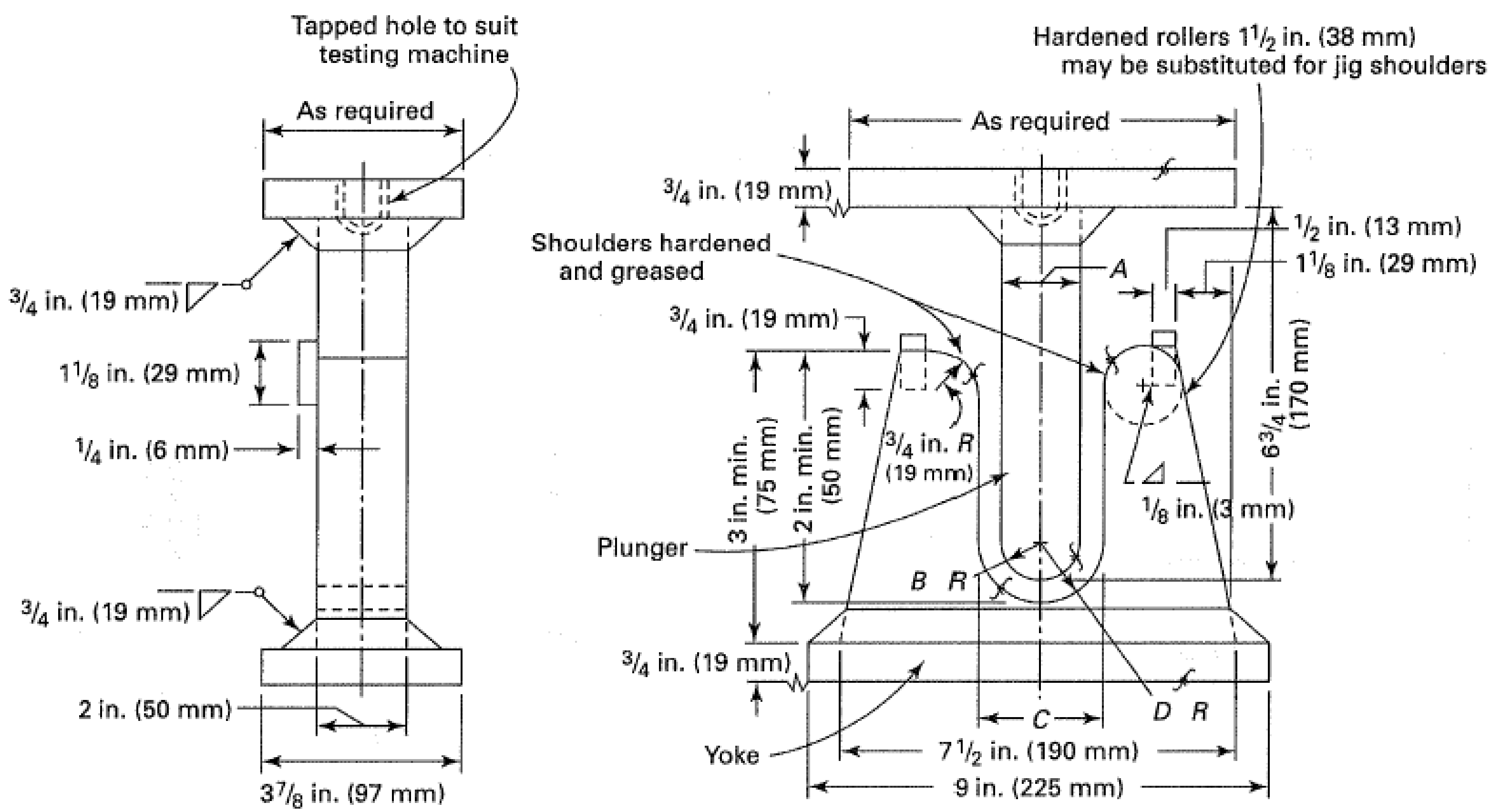


T, in. (mm)	Y, in. (mm): P-No. 23, F-No. 23, or P-No. 35	Y, in. (mm): All Other Metals
$\frac{1}{16} < \frac{1}{8}$ (1.5 < 3)	T	T
$\frac{1}{8}$–$\frac{3}{8}$ (3–10)	$\frac{1}{8}$ (3)	T
$> \frac{3}{8}$ (10)	$\frac{1}{8}$ (3)	$\frac{3}{8}$ (10)

ASME Section IX – QW-160 Guided Bend Test

- QW-162.1, Bend Test Jigs

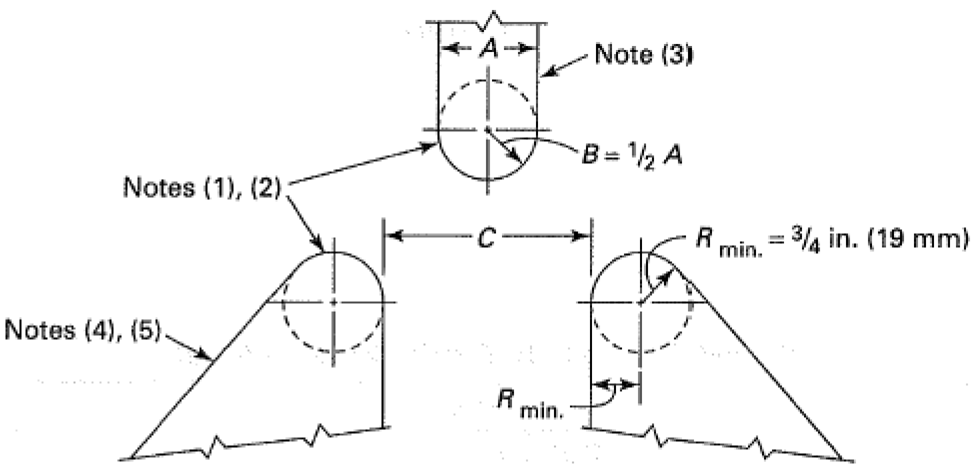
QW-466.1 TEST JIG DIMENSIONS



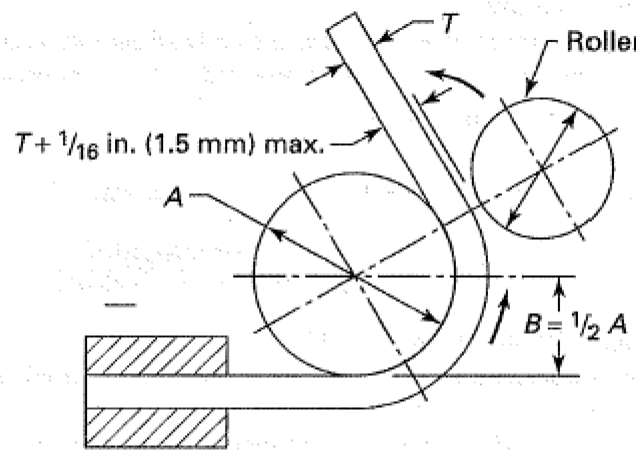
ASME Section IX – QW-160 Guided Bend Test

- QW-162.1, Bend Test Jigs

QW-466.2 GUIDED-BEND ROLLER JIG



QW-466.3 GUIDED-BEND WRAP AROUND JIG



ASME Section IX – QW-160 Guided Bend Test

- The dimensions of the bend test jig depend on the material that is being bent

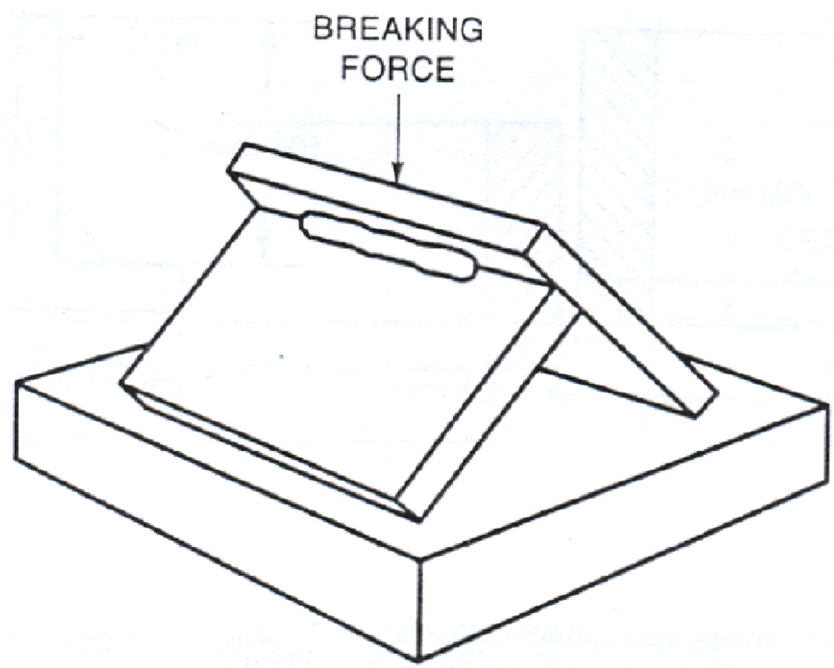
Material	Thickness of Specimen, in.	A, in.	B, in.	C, in.	D, in.
Customary Units					
P-No. 23 to P-No. 21 through P-No 25; P-No. 21 through P-No. 25 with F-No. 23; P-No. 35; any P-No. metal with F-No. 33, 36, or 37	$\frac{1}{8}$ $t = \frac{1}{8}$ or less	$2\frac{1}{16}$ $16\frac{1}{2}t$	$1\frac{1}{32}$ $8\frac{1}{4}t$	$2\frac{3}{8}$ $18\frac{1}{2}t + \frac{1}{16}$	$1\frac{3}{16}$ $9\frac{1}{4}t + \frac{1}{32}$
P-No. 11; P-No. 25 to P-No. 21 or P-No. 22 or P-No. 25	$\frac{3}{8}$ $t = \frac{3}{8}$ or less	$2\frac{1}{2}$ $6\frac{2}{3}t$	$1\frac{1}{4}$ $3\frac{1}{3}t$	$3\frac{3}{8}$ $8\frac{2}{3}t + \frac{1}{8}$	$1\frac{11}{16}$ $4\frac{1}{3}t + \frac{1}{16}$
P-No. 51; P-No. 49	$\frac{3}{8}$ $t = \frac{3}{8}$ or less	3 $8t$	$1\frac{1}{2}$ $4t$	$3\frac{7}{8}$ $10t + \frac{1}{8}$	$1\frac{15}{16}$ $5t + \frac{1}{16}$
P-No. 52; P-No. 53; P-No. 61; P-No. 62	$\frac{3}{8}$ $t = \frac{3}{8}$ or less	$3\frac{3}{4}$ $10t$	$1\frac{7}{8}$ $5t$	$4\frac{5}{8}$ $12t + \frac{1}{8}$	$2\frac{5}{16}$ $6t + \frac{1}{16}$
All others with greater than or equal to 20% elongation	$\frac{3}{8}$ $t = \frac{3}{8}$ or less	$1\frac{1}{2}$ $4t$	$\frac{3}{4}$ $2t$	$2\frac{3}{8}$ $6t + \frac{1}{8}$	$1\frac{3}{16}$ $3t + \frac{1}{16}$
Materials with 3% to less than 20% elongation	t = [see Note (b)]	$32\frac{7}{8}t$ max.	$16\frac{7}{16}t$ max.	$A + 2t + \frac{1}{16}$ max.	$\frac{1}{2}C + \frac{1}{32}$ max.

Guided Bend Test – Acceptance Criterion

- Bend Test per AWS D1.1
  - 4.8.3.3 Acceptance Criteria for Bend Test
    - No discontinuities greater than 1/8” in any direction
    - The sum of all discontinuities greater than 1/32” but less than 1/8” should not exceed 3/8”
    - No corner cracks greater than 1/4” with no visible evidence of slag or other fusion discontinuity
- Bend Test per ASME Section IX
  - QW-163 Acceptance Criteria – Bend Test
    - No discontinuities greater than 1/8” in any direction
    - Corner cracks shall not be considered unless there is evidence of weld defect

Fillet Weld Break Test

- Summary of Method
  - One leg of a T-joint is bent upon the other so as to place the root of the weld in tension.
  - The load is maintained until the legs of the joint come into contact with each other or the joint fractures
- Significance
  - To determine the soundness of fillet welded joints



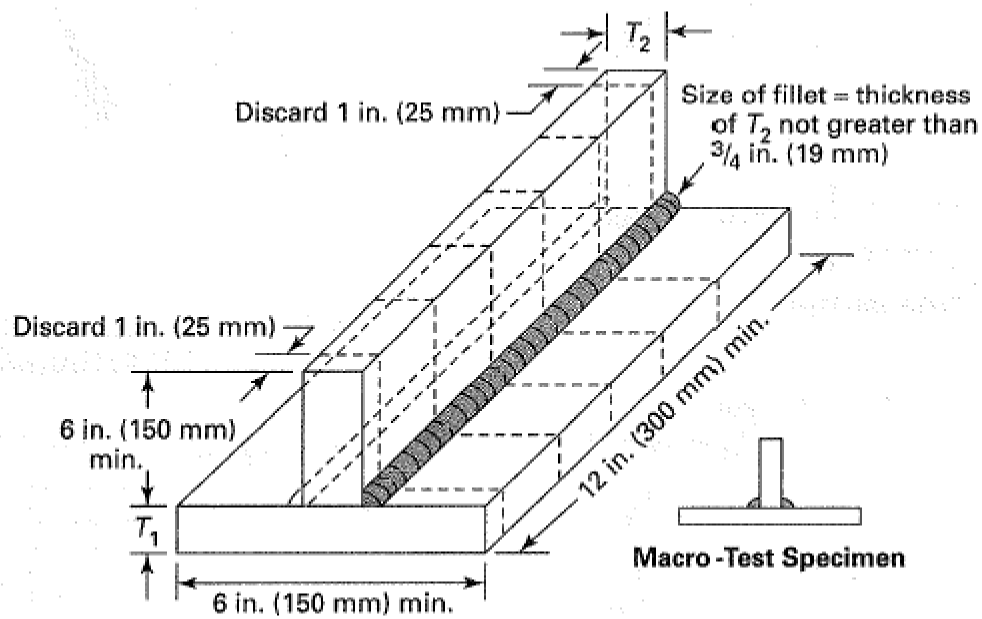
Fillet Weld Break Test Procedure

- A force as shown or other forces causing the root of the weld to be in tension shall be applied to the specimen
- The load shall be increased until the specimen fractures or bends flat upon itself
- If the specimen fractures, the fracture surfaces shall be examined visually to the criteria of the applicable standard

ASME Section IX – QW-180 Fillet Weld Test

QW-462.4(a) FILLET WELDS IN PLATE — PROCEDURE

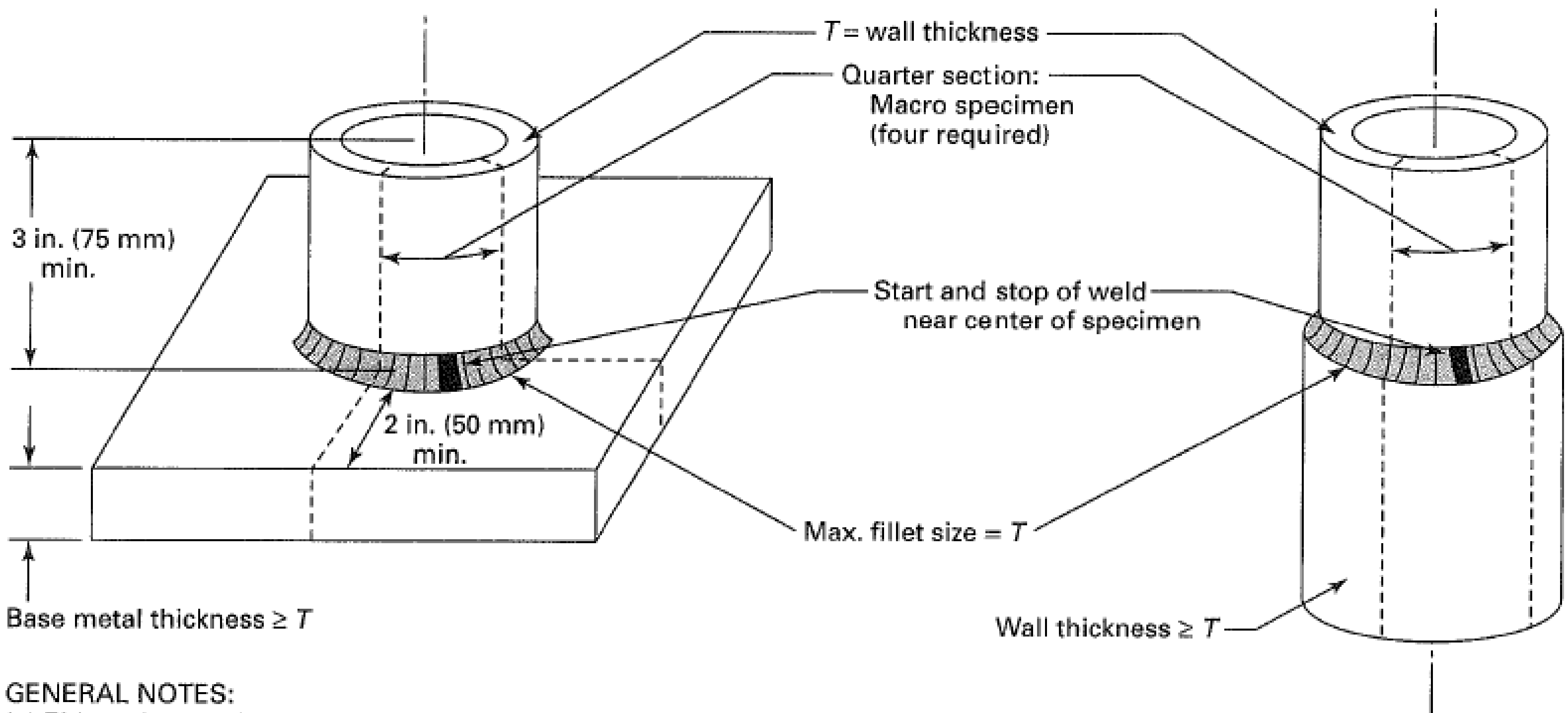
T_1	T_2
$^1/_8$ in. (3 mm) and less	T_1
Over $^1/_8$ in. (3 mm)	Equal to or less than T_1, but not less than $^1/_8$ in. (3 mm)



GENERAL NOTE: Macro-test — the fillet shall show fusion at the root of the weld but not necessarily beyond the root. The weld metal and heat-affected zone shall be free of cracks.

ASME Section IX – QW-180 Fillet Weld Test

QW-462.4(d) FILLET WELDS IN PIPE — PROCEDURE



GENERAL NOTES:
(a) Either pipe-to-plate or pipe-to-pipe may be used as shown.
(b) Macro test:
  (1) The fillet shall show fusion at the root of the weld but not necessarily beyond the root.
  (2) The weld metal and the heat-affected zone shall be free of cracks.

Fillet Weld Break Test – Acceptance Criteria

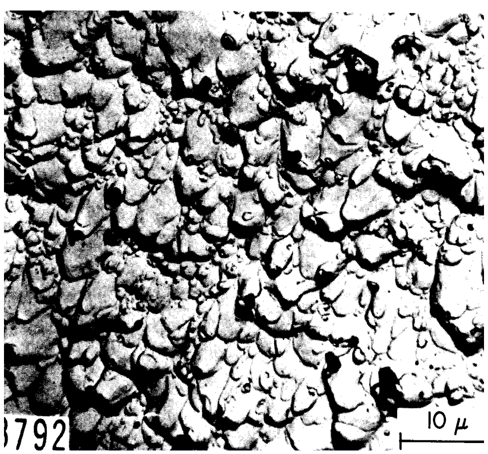
- Fillet Weld Break Test per AWS D1.1
  - 4.30.4.1 Acceptance Criteria for Fillet Weld Break Test
    - Reasonably uniform appearance and free of overlap, cracks and undercut within acceptable limits of visual inspection
    - The broken specimen shall be flat upon itself or the fracture surface shall show complete root fusion with no inclusion or porosity larger than 3/32” in greatest dimension
    - The sum of the greatest dimensions of all inclusions and porosity shall not exceed 3/8” in the 6” long specimen.
- Fillet Weld Break Test per ASME Section IX
  - QW-182 Fracture Test
    - The fracture surface shall show no evidence of cracks or incomplete root fusion
    - The sum of inclusions and porosity shall not exceed 3/8” or 10% of the section

Fracture Toughness Tests – Summary of Methods

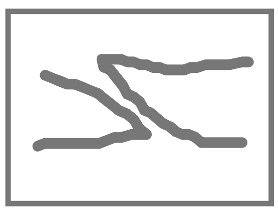
- Charpy V-notch - Impact on V-notched specimen
- Dynamic Tear - Three point bending of U-notched specimen loaded at high strain rate by strike
- Plane-Strain Fracture Toughness - Plane-strain critical fracture toughness value obtained at slow loading rates on compact tension specimen with maximum constraint (thick specimen with deep crack) resulting in brittle fracture with little or no deformation
- Drop-Weight Nil Ductility Transition Temperature – Drop weight impact on flat notched specimen with maximum fracture stress at material’s yield stress

Fracture Toughness Test – Significance

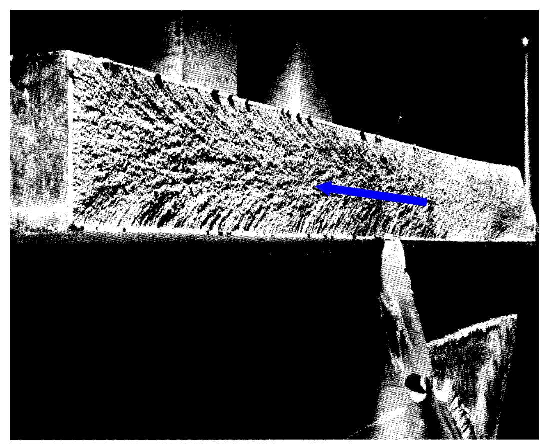
- Provides a measure of resistance to crack initiation or propagation or both
- The same welding process, procedure, and weld cooling rates must be used for the test sample and the structure
- Fracture toughness of steels is sensitive to service temperature



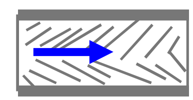
Shear Rupture Dimples

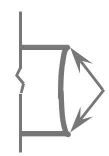


Shear Deformation



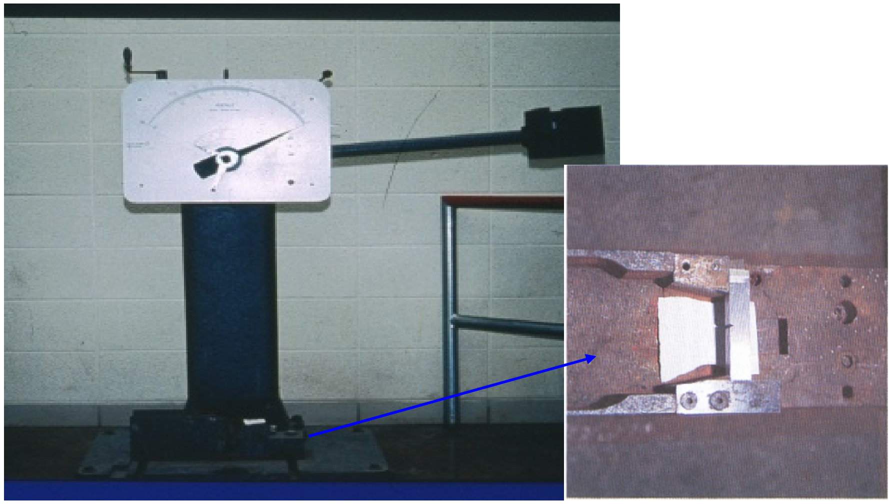
Photograph of Typical Brittle Fracture Surface



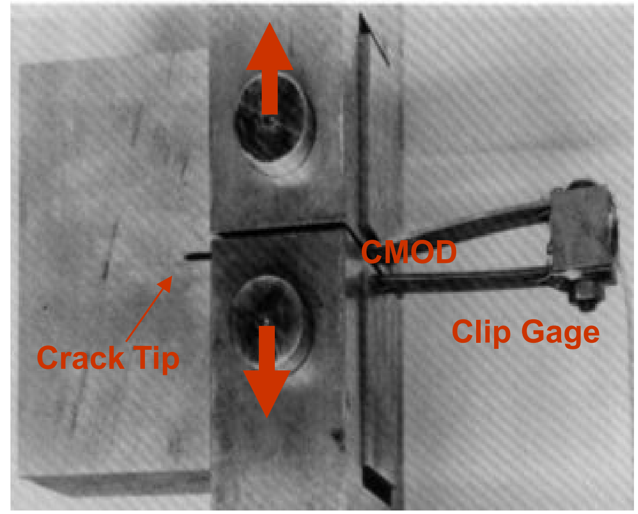


Chevron Markings

Fracture Toughness Test Apparatus

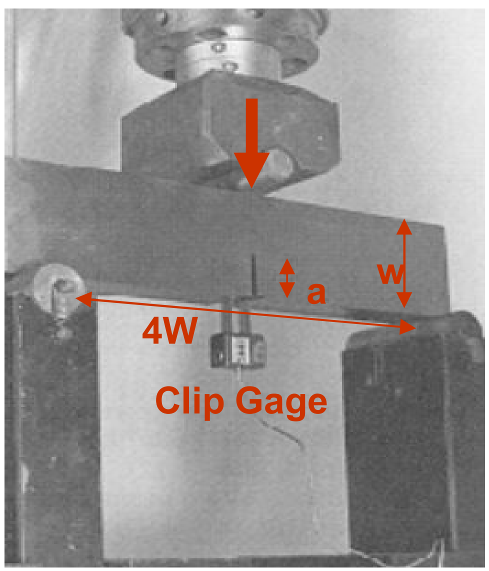


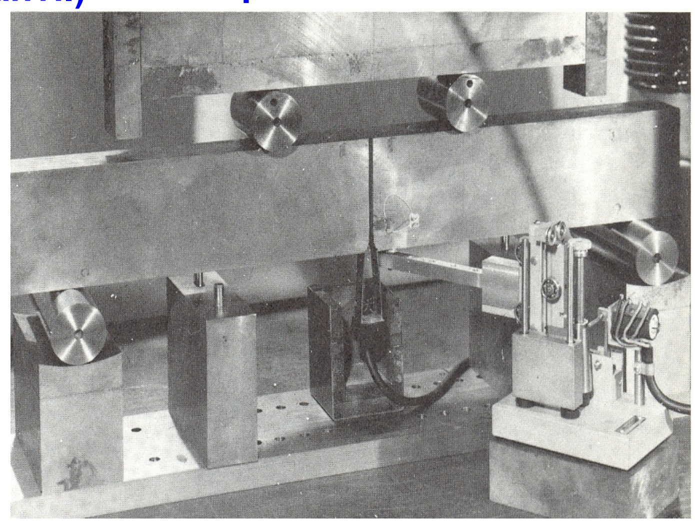
Charpy V-Notch Test (right: placement of specimen in anvil)



Compact Tension Test

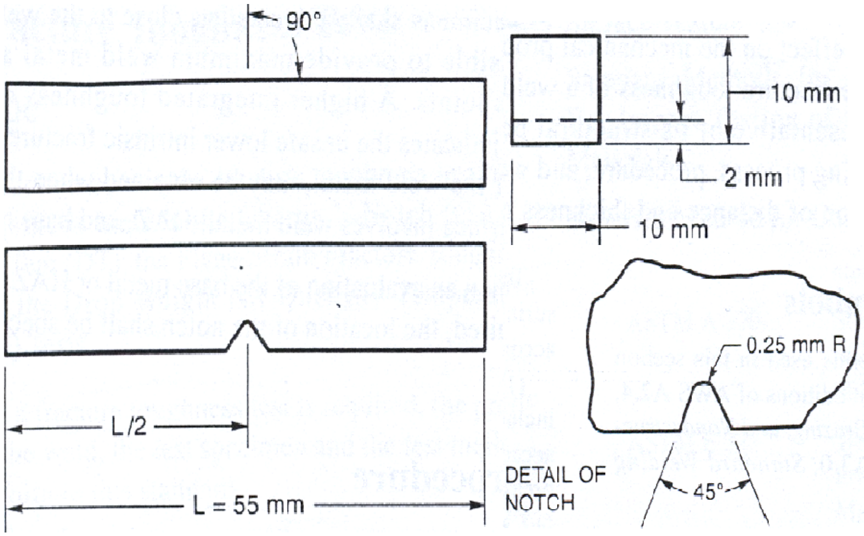
Three-Point Bending Test

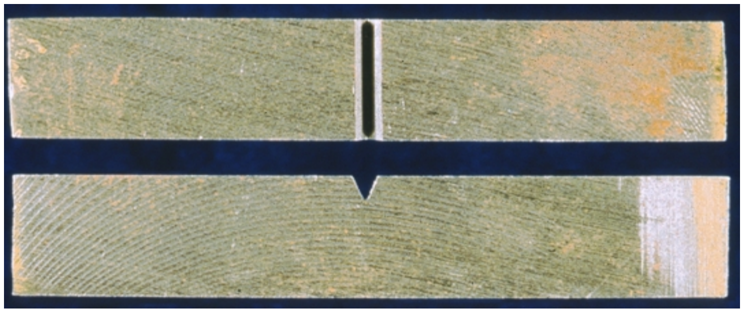




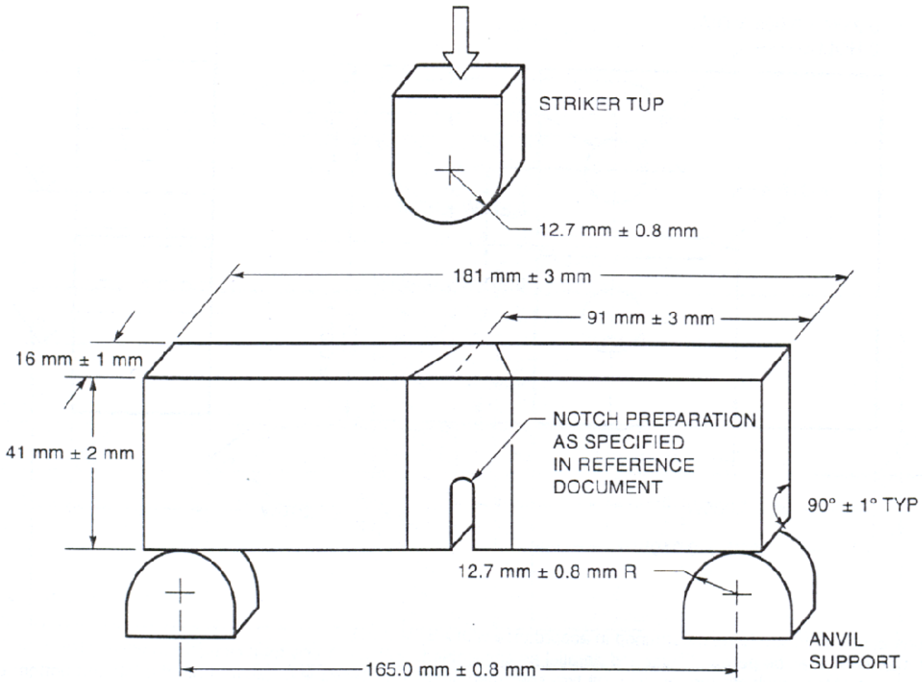
Four-Point Bending Test

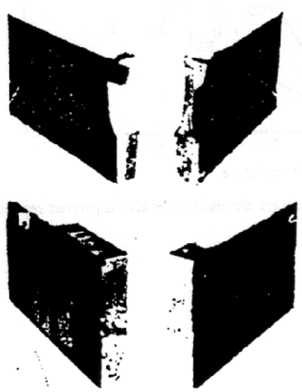
Fracture Toughness Test Specimens





Charpy V-Notch Impact Specimen



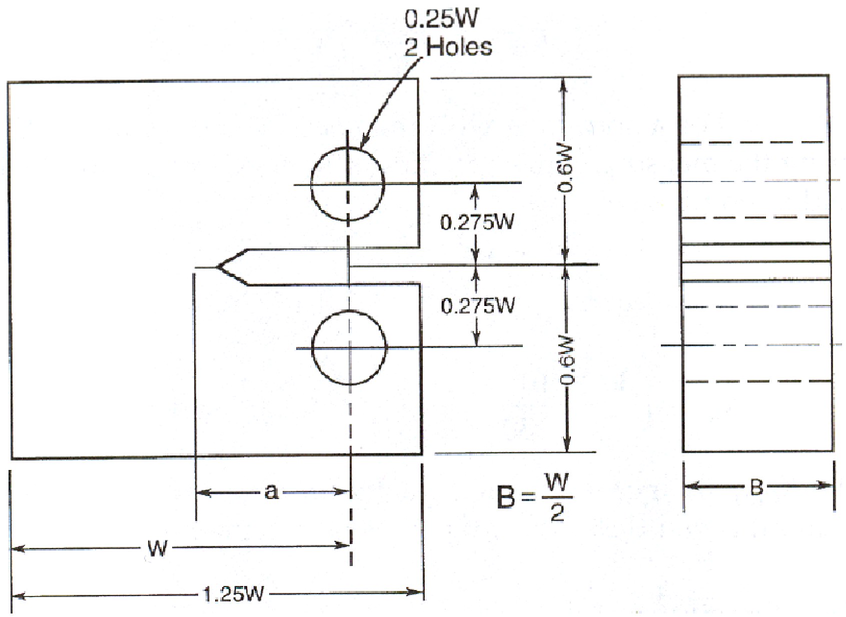


Dynamic Tear Test Specimen

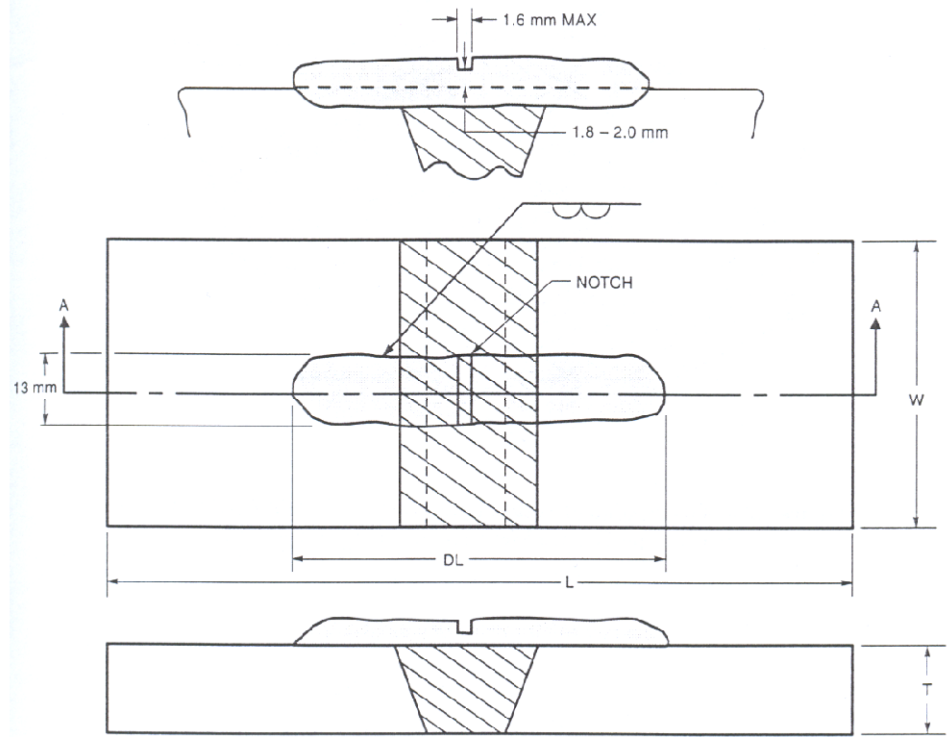
Fracture Toughness Test Specimens

Crack Driving Force: Stress Intensity Factor, K_I

$$K_I = \sigma\sqrt{\pi a} \bullet correction..factor$$

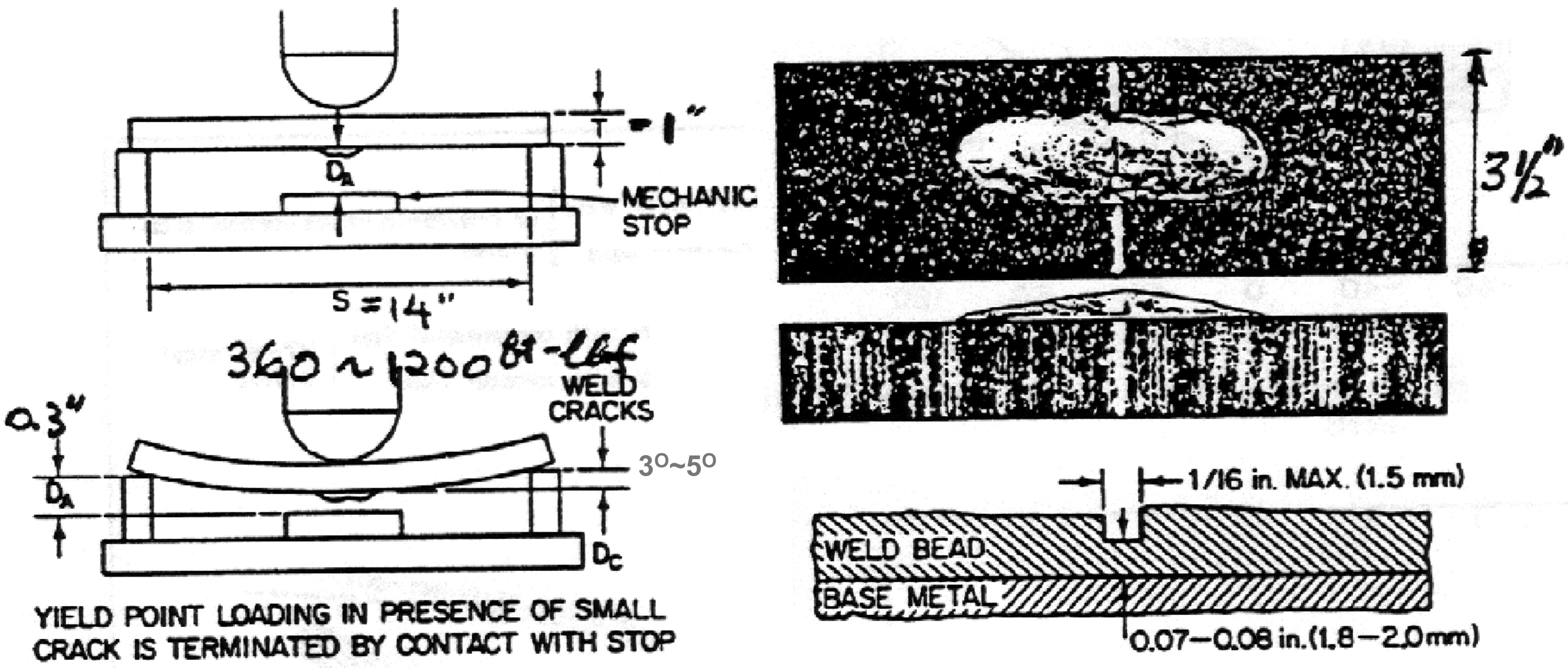


Compact Tension Fracture Toughness Test Specimen



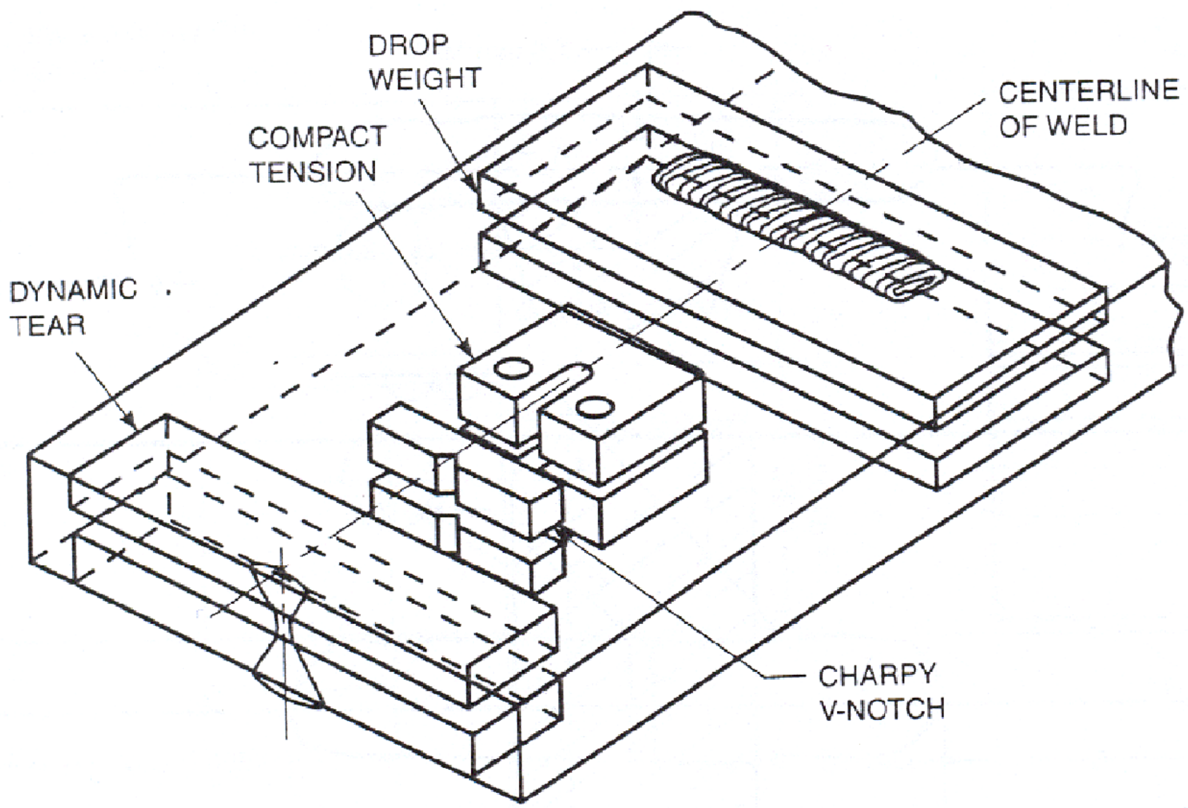
Drop Weight Nil-Ductility Temperature Test Specimen

Fracture Toughness Test Apparatus



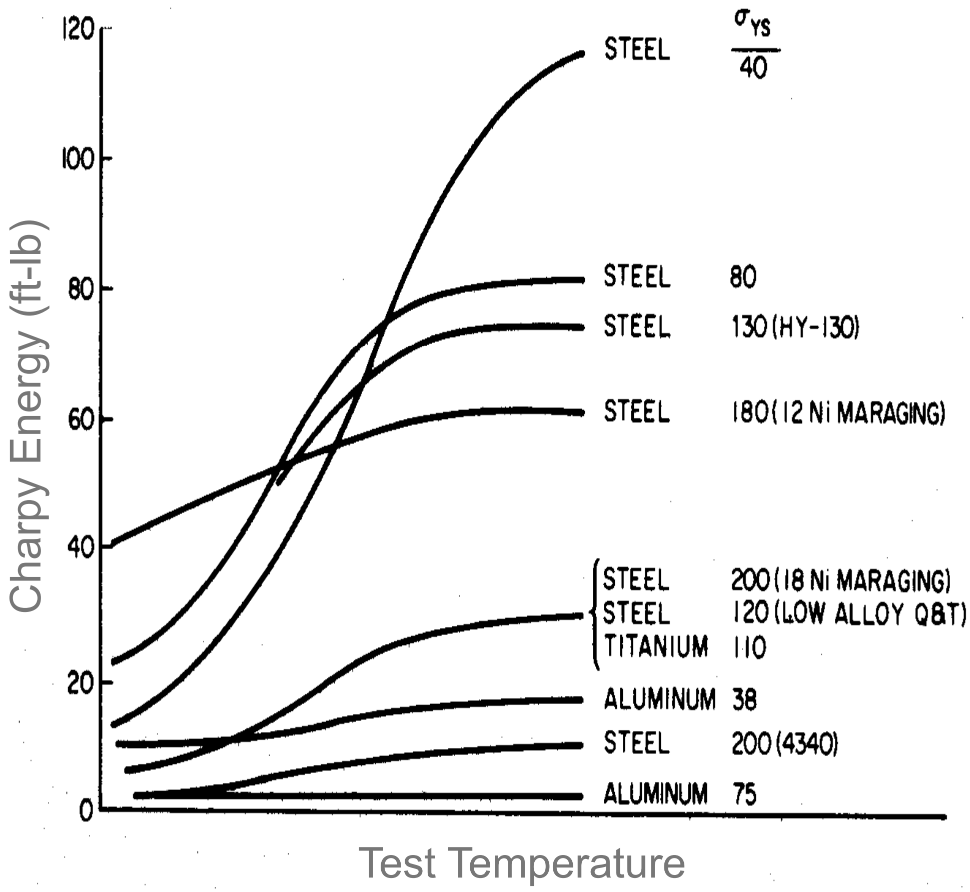
Drop-Weight Nil Ductility Transition Temperature Test

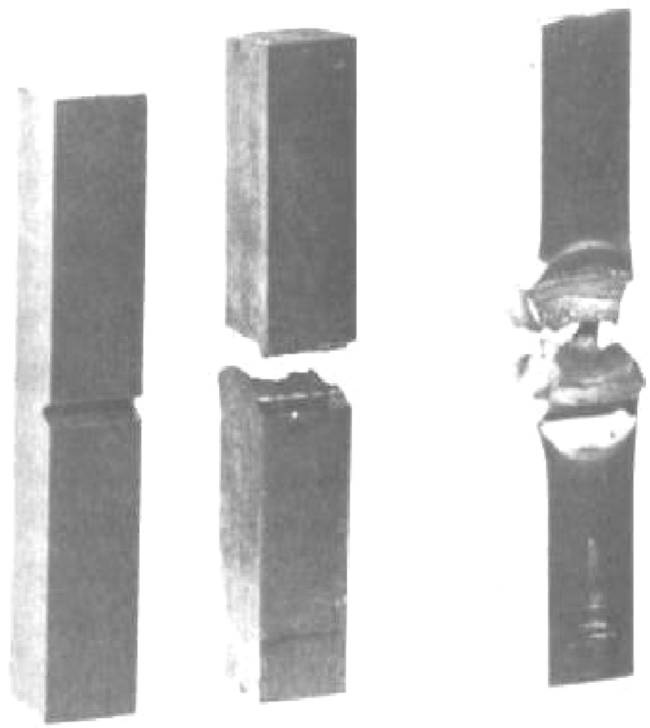
Fracture Toughness Test Procedure



Orientation of Weld Metal Fracture Toughness Specimen in a Double-Groove Weld Thick Section Weldment

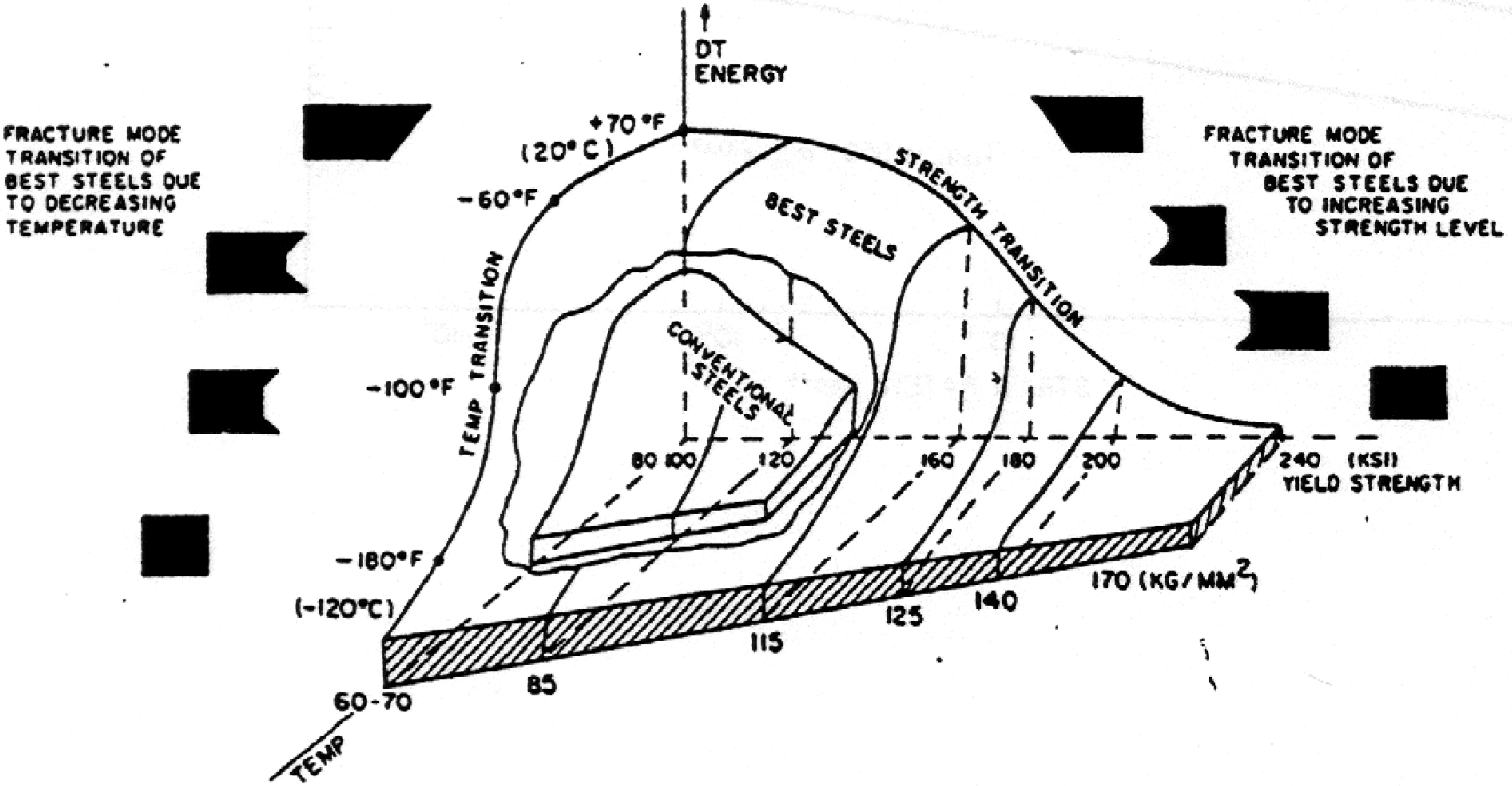
Fracture Toughness Test Acceptance Criteria





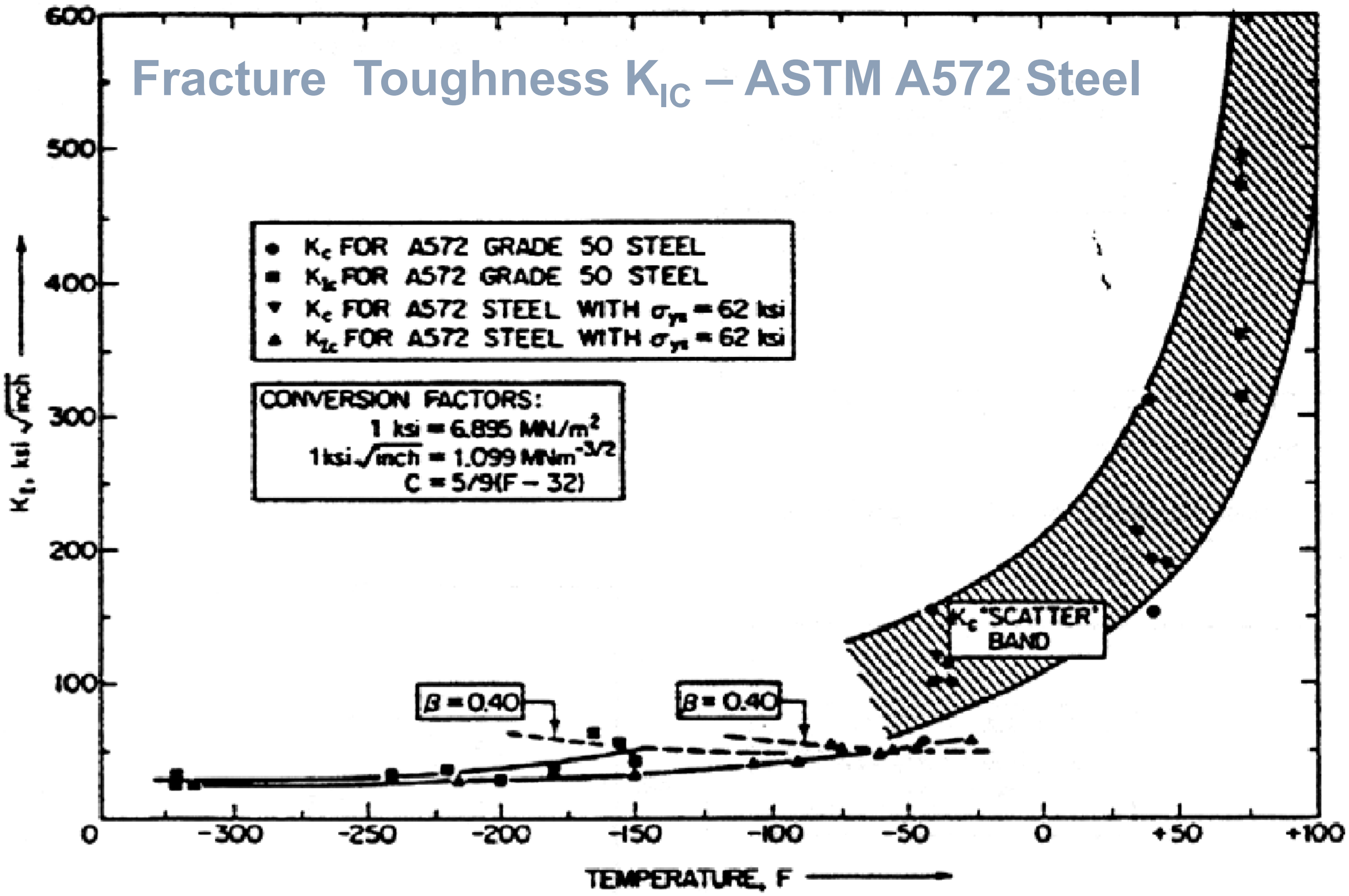
Charpy V-Notch Test Results

Fracture Toughness Test Acceptance Criteria



Dynamic Tear Test Results

Fracture Toughness Test Acceptance Criteria



Compact Tension Test Results