Advances in Welding and Joining Technologies

Advances in welding and joining technologies
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Module 6

Welding Metallurgy

- ✓ Chemical reactions in welding
- ✓ Residual stress and distortion
- ✓ Solidification in welding
- ✓ Weld microstructure
- ✓ Phase transformation
- ✓ Solidification cracking
- ✓ Heat treatment of weld joint

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Introduction

- Effect of structural changes that might occur while joining two similar or dissimilar materials
- Weld quality depends upon several parameters – welding metallurgy
- Selection of proper shielding medium is necessary to control various welding defects
- Suitable welding process - reduces residual stress generation and distortion
- Distortion - dimensional accuracy
- Solidification mode - final microstructure of the welded joint
- Microstructure - sound mechanical strength
- Microstructure - can be developed in the fusion zone by various grain structure control mechanisms

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Chemical Reactions in Welding

- Gas–metal reactions
- Slag–metal reactions

- ✓ High temperature during the welding promotes chemical reaction with environmental gases
- ✓ Gases get dissolved in weld pool and form pin hole or porosity
- ✓ Can combine with elements to form inclusions

Chemical reaction can be controlled by

- Using proper shielding gas
- By cleaning base metal and electrode before welding

- Chemical reactions finally affects the weld metal composition and mechanical properties

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Chemical Reactions in Welding

Investigation: Properties degradation of low carbon steel weld without shielding gas **[Ref: A. A. Erokhin, Kinetics of Metallurgical processes in Arc welding, Mashinostroenie, 1964]**

Mechanical Properties	Base Metal	Weld Metal
Tensile Strength (N/mm^2)	390-440	334-390
Ductility (%)	25-30	5-10
Toughness (J/mm^2)	More than 147.0	4.9-24.5

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- ✓ High Oxygen (0.7%) and Nitrogen (0.2%) content in the weld
- ✓ These elements usually come from atmosphere, or from the moist or dirt on base metal surface
- ✓ Weld metal exhibits a much lower ductility and impact toughness

Chemical Reactions in Welding

Effect of Nitrogen, Oxygen, and Hydrogen on weld quality

	Nitrogen	Oxygen	Hydrogen
Steels	Increases strength but reduces toughness	Reduces toughness but improves it if acicular ferrite is promoted	Induces hydrogen cracking
Austenitic or duplex stainless steel	Reduces ferrite and promotes solidification cracking		
Aluminum		Forms oxide, films which can be trapped as inclusions	Forms gas porosity, and reduces strength and ductility
Titanium	Increases strength but reduces ductility	Increases strength but reduces ductility	

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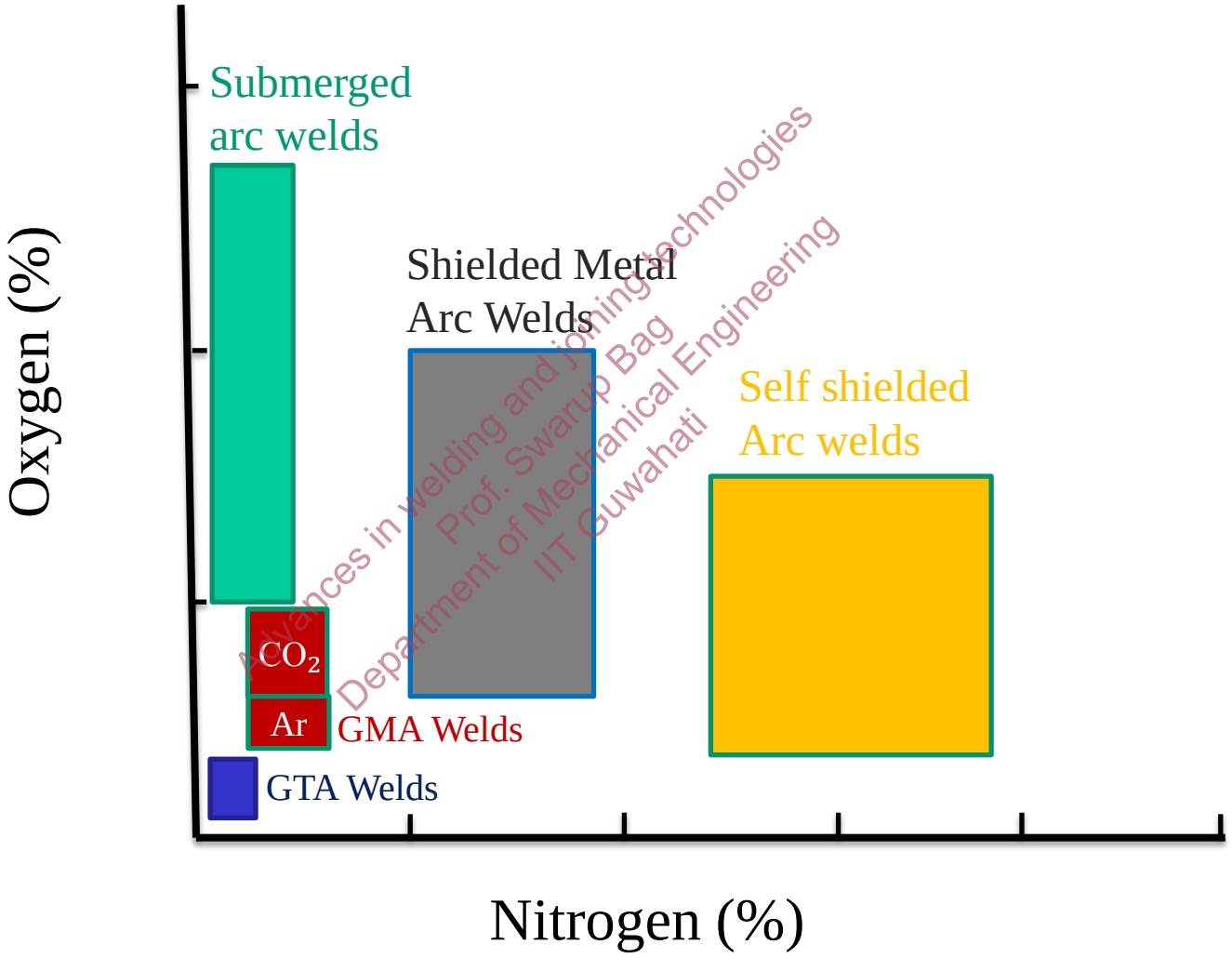
Chemical Reactions in Welding

Oxygen and nitrogen levels at arc welding processes



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SSAW – continuous consumable electrode

Chemical Reactions in Welding

Protection medium in common welding processes

Weld protection medium	Fusion welding process
Gas	GTAW, GMAW, PAW
Slag	Submerged arc, Electroslag
Gas and slag	Shielded metal arc, Flux-cored arc
Vacuum	Electron beam
Self-protection	Self-shielded arc

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- GTAW - Ar and He (Stable arc with less oxygen level)
- GMAW - CO_2 (At high temperature it dissolves into CO and O which increases the weld oxygen level)
- SAW - High oxygen level due to the presence of SiO_2 in the flux

Chemical Reactions in Welding

❖ Gas – Metal Reaction

- Reactions that take place at the gas - liquid interface
- Dissolution of nitrogen, oxygen, and hydrogen in liquid metal

(i) Nitrogen – Metal reactions

When molten steel exposes to N_2, result in dissolution of Nitrogen atoms in the molten steel

$$\frac{1}{2}N_2 \text{ (gas)} = \underline{N} \text{ (Dissolved in iron)}$$

weight percentage of dissolved nitrogen [$\underline{N}$]at a given temperature T can be determined by

$$[\underline{N}] = k\sqrt{P_{N_2}} \qquad \text{(Sieverts Law)}$$

where k – equilibrium constant

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Chemical Reactions in Welding

$$\ln k = \ln\left(\frac{[\underline{N}]}{\sqrt{P_{N_2}}}\right) = \frac{-\Delta G^0}{RT}$$

Free energy of Nitrogen in liquid iron

$$\Delta G^0 = 860 + 5.71\ T \text{ cal/mole } \underline{N} \text{ (Henry's law)}$$

ΔG^0- Free energy of Nitrogen in liquid iron
P_{N_2} - partial pressure (in atmospheres) of N_2 above the molten metal
R – characteristic gas constant

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(ii) Oxygen- Metal Reactions

- Oxygen from atmosphere due to insufficient shielding
- Excess use of oxygen in oxy-acetylene welding
- Oxygen containing inert shielding gases

Chemical Reactions in Welding

CO_2 can decompose - at high temperature of the welding arc

CO_2 (gas)= CO (g) + $\frac{1}{2}$ CO (g)

CO (gas)= C (s) + $\frac{1}{2}$ O_2

Solution of oxygen in liquid iron obeys Sievert's law

$\frac{1}{2} O_2$ (gas) = $\underline{O}$ (Dissolved in iron)

ΔG^0 = -28000- 0.69 T cal/mole $\underline{N}$

Weight percentage of $\underline{O}$ in liquid iron can be find out by

Log [O] = - 6320/T + 2.73

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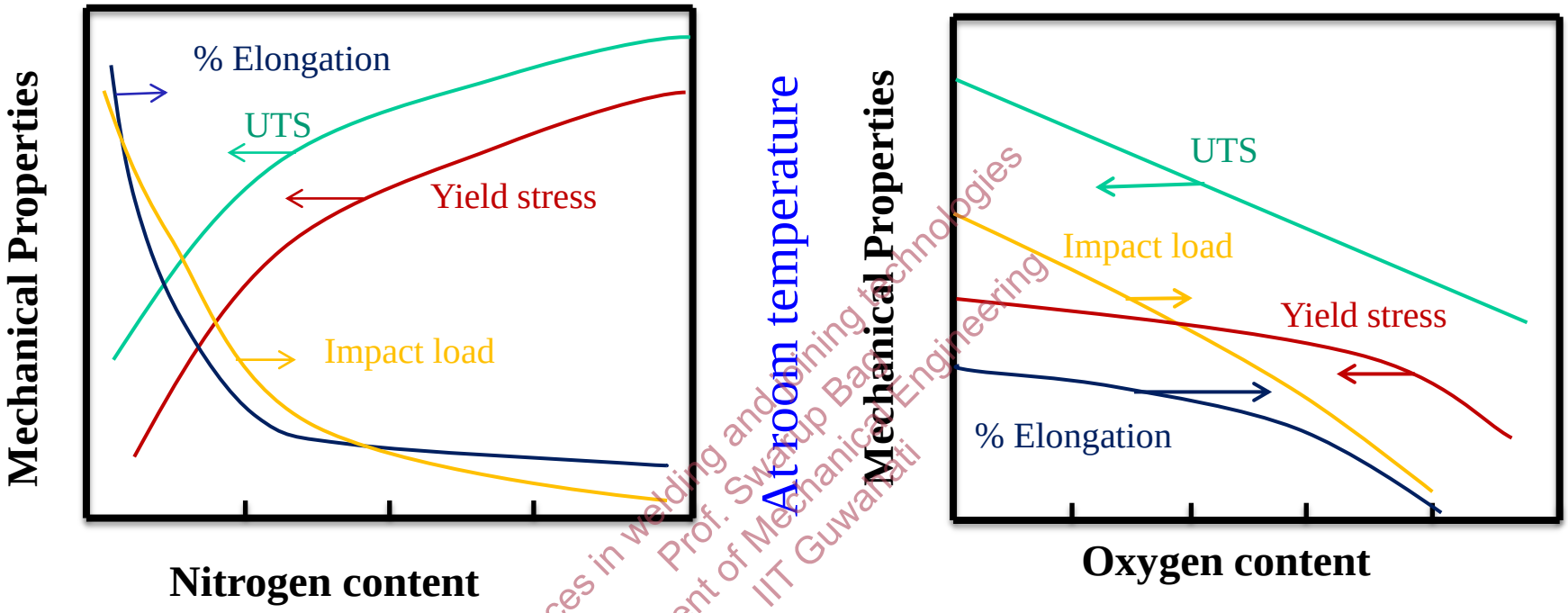
Chemical Reactions in Welding



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(iii) Hydrogen- Metal Reactions

Presence of hydrogen in steels - cause hydrogen cracking

- Combustion products in oxyfuel welding
- Moisture or grease on the workpiece surface or electrode
- Hydrogen in workpiece or shielding gas

Chemical Reactions in Welding

Hydrogen level can be reduced by

- Avoiding hydrogen-containing shielding gases
- Drying the electrode and flux to remove moisture
- Cleaning the filler wire and workpiece to remove grease

The solution of hydrogen in liquid iron obeys Sieverts law

$\frac{1}{2} H_2$ (gas) = $\underline{H}$ (Dissolved in iron)

$\Delta G^0 = 7490 - 10.81\ T$ cal/mole $\underline{H}$

$$\log k = -\frac{1637}{T} + 2.36$$

where $k = \frac{[H]}{\sqrt{P_{H_2}}}$

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Chemical Reactions in Welding

Slag–metal reactions

Proper welding flux helps to control the weld composition and protect it from atmosphere

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Halide type fluxes such as CaF_2–NaF, CaF_2–$BaCl_2$–NaF

Oxygen free - used for welding titanium and aluminum alloys

Halide oxide type fluxes: CaF_2–CaO–Al_2O_3

Slightly oxidizing - used for welding high-alloy steels

Oxide type fluxes: MnO–SiO_2

Welding low-carbon or low-alloy steels

Chemical Reactions in Welding

Oxides in a welding flux

SiO_2, TiO_2

CaO, MgO

Al_2O_3, Fe_2O_3

Thermochemical reaction takes place

At high-temperature - oxides produce oxygen

SiO_2 and MnO can decompose as follows

$$SiO_2 = SiO\,(g) + \frac{1}{2} O_2\,(g)$$

$$MnO = Mn\,(g) + \frac{1}{2} O_2\,(g)$$

Oxidation by Oxygen in Metal

$$\underline{Ti} + 2\underline{O} = (TiO_2)$$

$$2Al + + 2\underline{O} = (Al_2O_3)$$

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Chemical Reactions in Welding

Electrochemical Reactions

Reactions occur at the electrode tip–slag interface in DCEP polarity

or the weld pool–slag interface in the DCEN polarity

$$M(metal) + nO^{2-}(slag) = MO_n + 2ne^-$$

$$O^{2-}(slag) = O(metal) + 2e^-$$

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Cathodic reactions

$M^{2+} + 2e^- = M(metal)$ — Reduction of metallic cations from the slag

$Si^{4+}(slag) + 4e^- = Si(metal)$

$O(metal) + 2e^- = O^{2-}(slag)$ — Removal (refining) of oxygen from the metal

Residual stress and distortion

- Change in solidified structure and mechanical constraints
- Non-uniform temperature changes - thermal strain and stress
- Exists in the body

- ✓ Non uniform heating and cooling
- ✓ Difference in expansion coefficients
- ✓ Mechanical incompatibility of the different components
- ✓ Structural deformation from metal working
- ✓ Structural heterogeneity in micro-scale
- ✓ Various surface treatment

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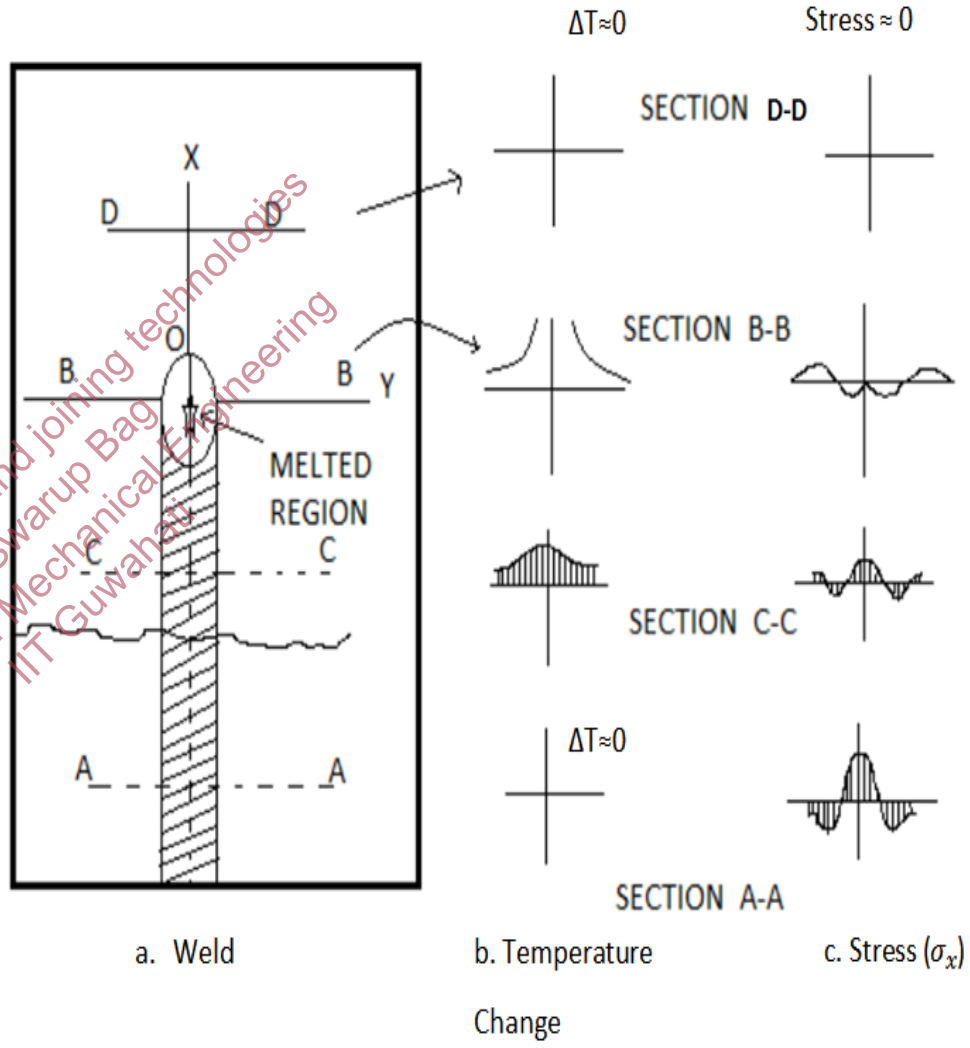
Residual stress and distortion

Residual stresses - cause serious problems like hydrogen cracking and stress corrosion cracking

Various techniques like pre and post weld heat treatment, peening and vibration are used for stress relief of the weldment

Section D-D: not affected by heat input - Thermally induced stress is zero

Section B-B: underneath the heat source; σ_x is close to zero



Change in temperature and stress (σ_x) at various locations in the welding direction

Ref: Weisman, Welding Handbook,7th ed., Vol. 1,1976.

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Residual stress and distortion

- Away from heat source: stresses are compressive since the expansion is restrained by the surrounding metal of lower temperatures
- Farther away from the weld: σ_x is tensile, and σ_x is balanced with compressive stresses in areas near the weld

Section C–C: the weld metal and the adjacent base metal have cooled - tendency to contract, thus producing tensile stresses

Section A–A: the weld metal and the adjacent base metal have cooled and contracted further - produce higher tensile stresses in regions near the weld and compressive stresses in regions away from the weld

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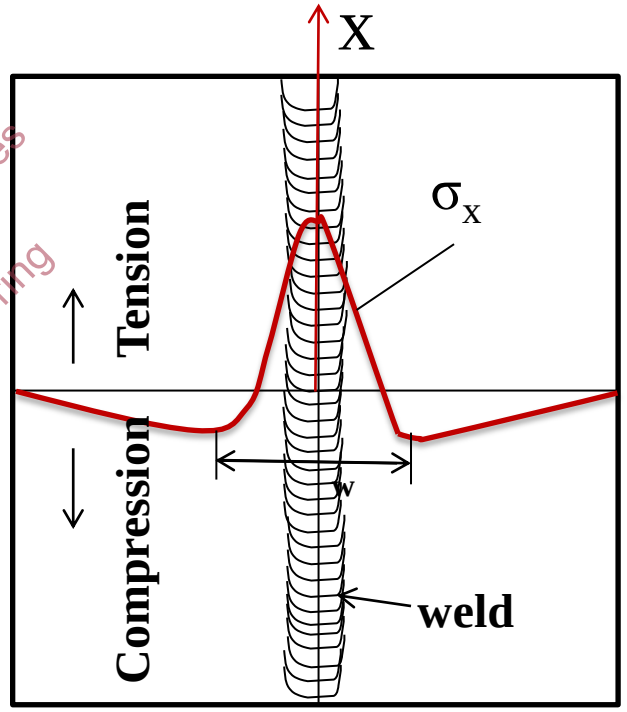
Analysis of Residual Stresses

According to Masubuchi and Martin, the distribution of the longitudinal residual stress σ_x can be written as

$$\sigma_x(y) = \sigma_m \left[1 - \left(\frac{y}{w}\right)^2\right] e^{-\frac{1}{2}(y/w)^2}$$

where σ_m is the maximum residual stress and w is the width of the tension zone σ_x.



Distributions of longitudinal (σ_x) residual stresses

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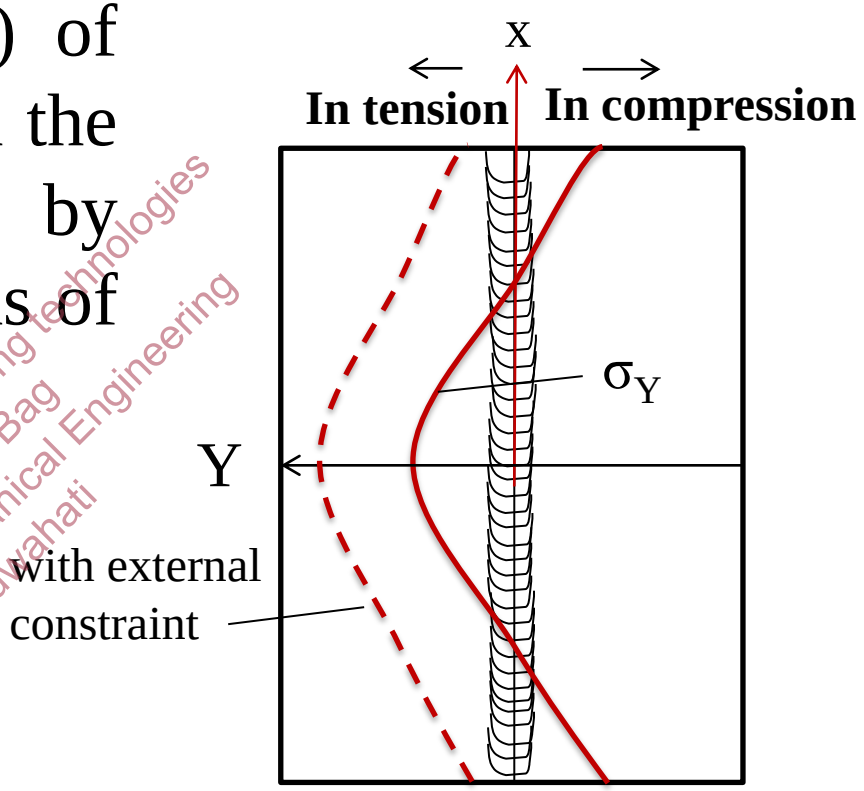
Residual stress and distortion

Transverse residual stress (σ_y) of low magnitude are produced in the middle part - balanced by compressive stresses at the ends of the weld

Lateral contraction of the joint is restrained - by an external constraint

approximately uniform tensile stresses are added along the weld as the reaction stress



Distributions of transverse (σ_y) residual stresses

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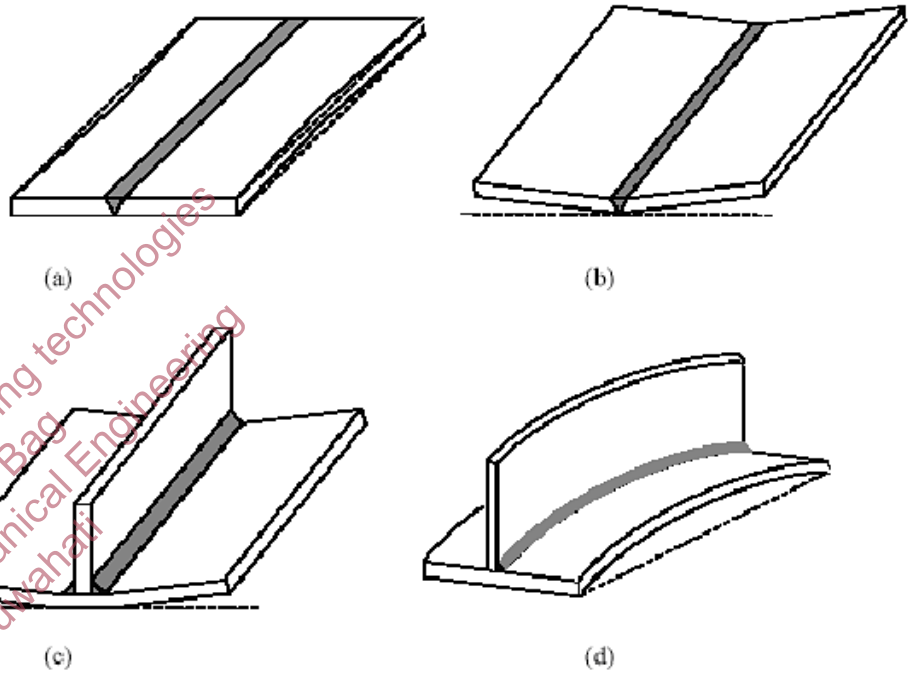
Distortion in weldment

Solidification shrinkage
Thermal contraction
Metallurgical changes
Boundary constraints

Angular distortion – during welding of thick and thin plates



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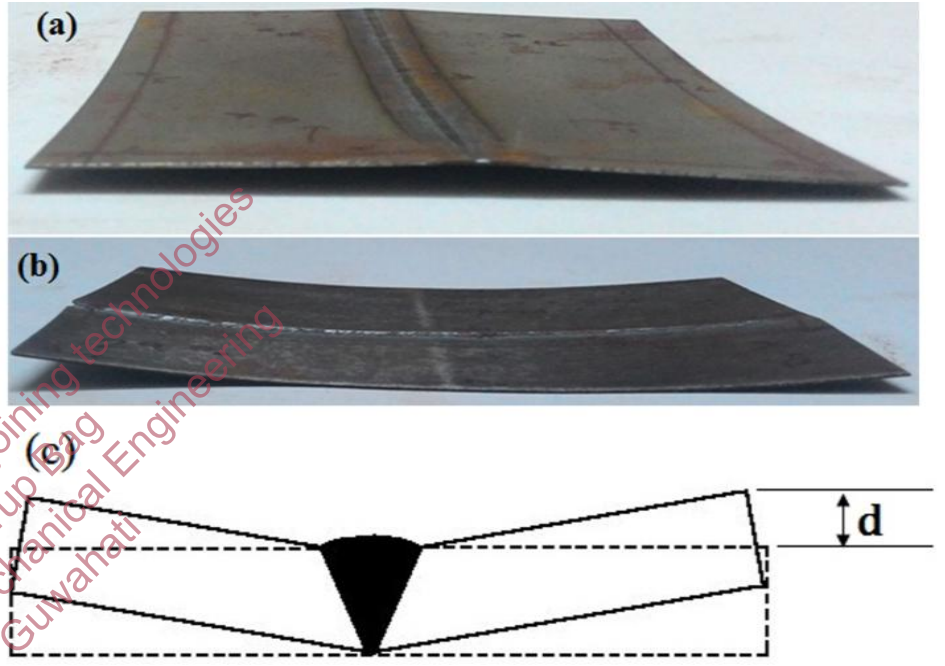
The welded component can shrink in the transverse direction as well as in longitudinal direction

(a) Transverse shrinkage in a Butt-Joint
(b) Angular change in a butt-joint
(c) Angular Change in a T-Joint
(d) Longitudinal distortion in fillet joint

Distortion in weldment

Remedies

- By reducing the weld metal volume
- Using electron or laser beam welding, angular distortion can minimized
- Placing welds about the neutral axis also helps to reduce distortion
- Following multi-path



Distortion: (a) transverse and (b) welding direction
(c) estimating the deflection in the butt joint

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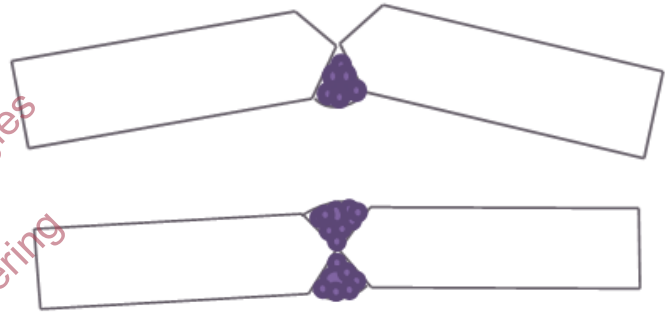
Distortion in weldment

Remedies

- ✓ Welding alternately on either side of the double-V joint is preferred
- ✓ By using elastic pre-springing angular changes can reduced
- ✓ Pre-heating, thermal management during welding
- ✓ Post weld heating reduce angular distortion



Effect of double-V joint and both side welding on reduction of weld distortion

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Solidification in welding

Solidification - an important role in defining the mechanical properties of welded joints

Mode of solidification - final shape and size of the weld microstructure

- Temperature of the weld pool falls below the liquidus temperature

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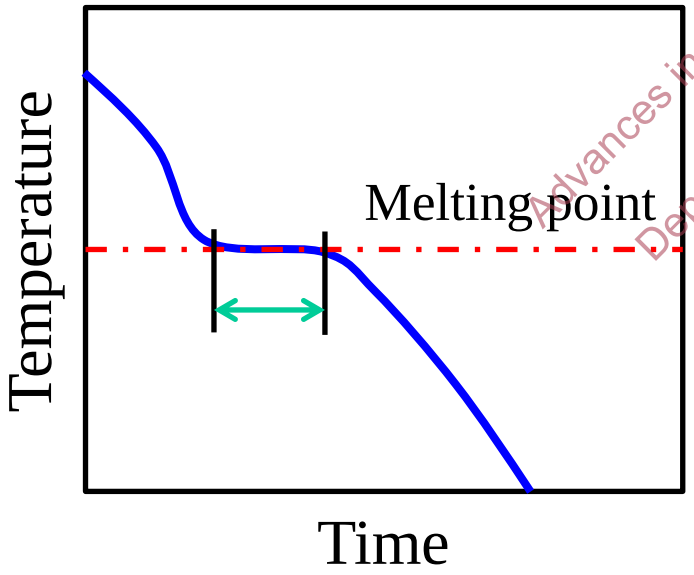
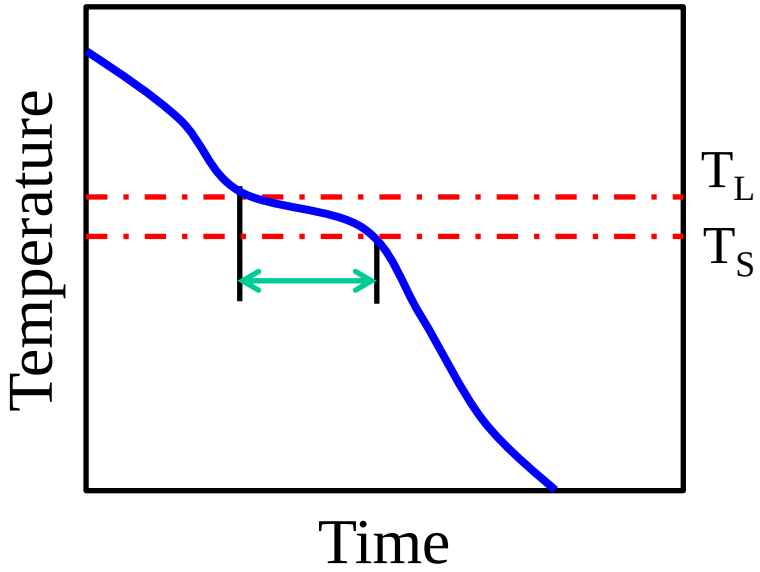


Pure metal

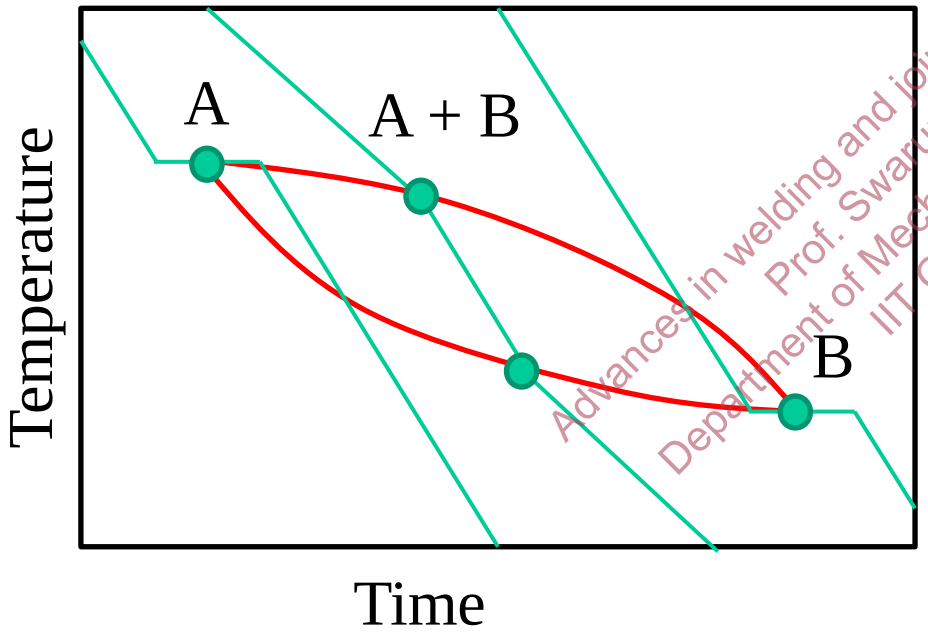
Cooling curve

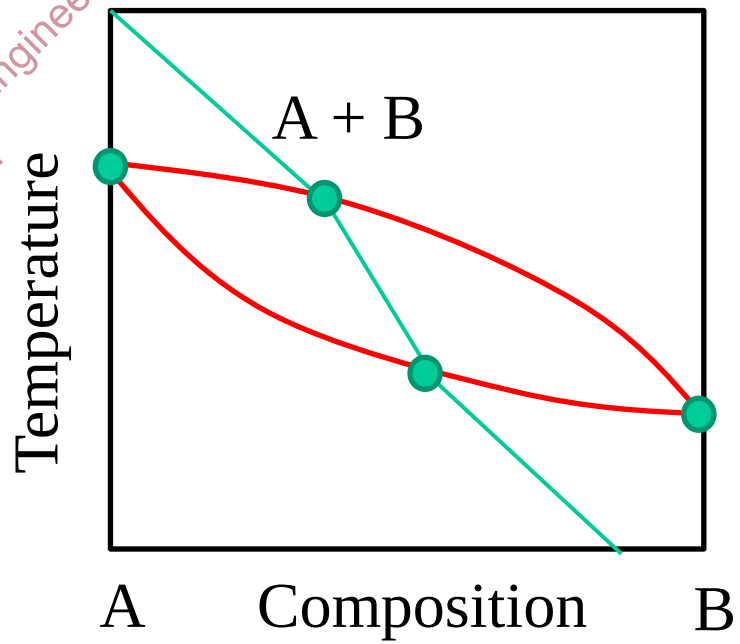


Alloy system

Solidification in welding

Cooling curve for binary alloy
- Completely soluble





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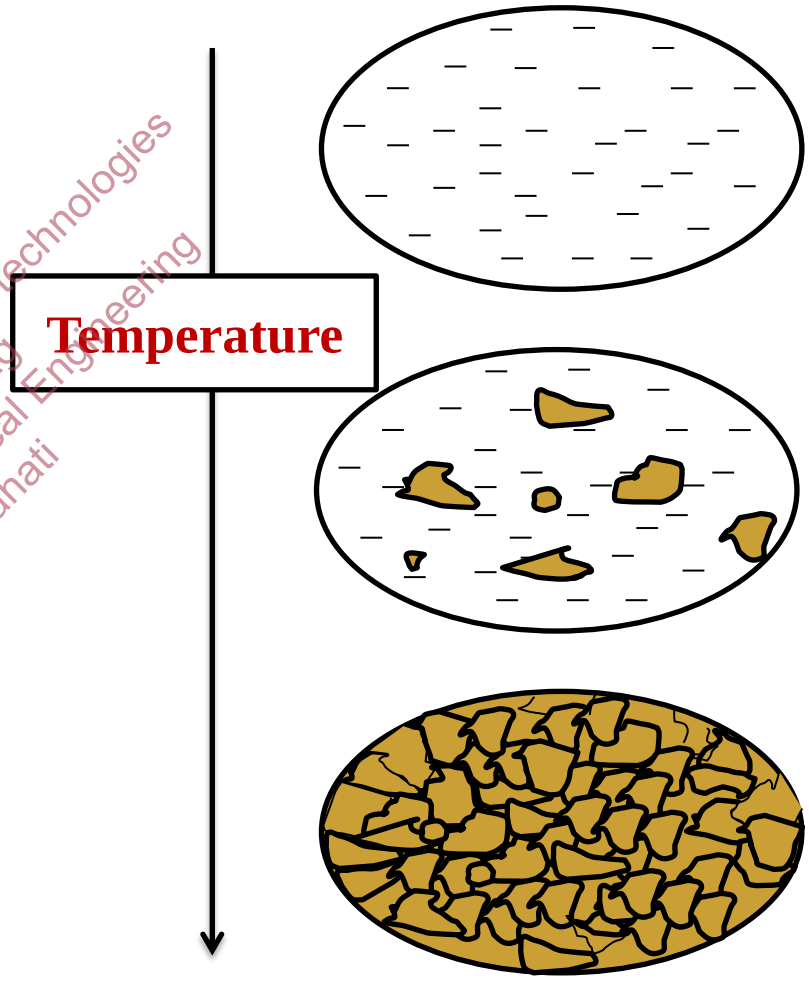
Solidification in welding

- ✓ Driving force is undercooling or Supercooling
- ✓ Phase transformation in two steps - Nucleation and Growth
- ✓ Nucleation involves the formation of small stable particles (nuclei) of the new phase from the liquid
- ✓ In the growth stage the stable nuclei's size increases as a result the parent phase disappear partially or fully



Phase change with temperature

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Solidification in welding

Progress of phase transformation:

Nucleation and Growth

- ✓ Homogeneous Nucleation
- ✓ Heterogeneous Nucleation

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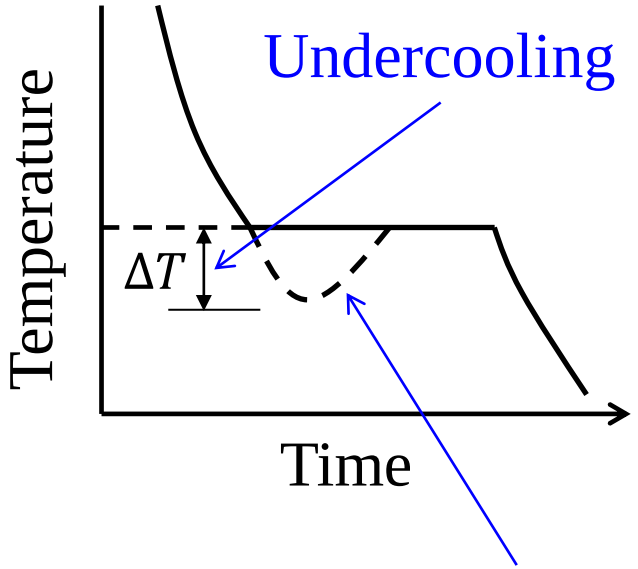
Homogeneous Nucleation

Formation of a critically sized solid from the liquid



Driving force: high undercooling without an external interface

Solidification in welding

Volume free energy – free energy difference between the liquid and solid phases

Surface energy – energy needed to create a surface for the spherical particles

Total free energy Change $\Delta G = 4/3\pi r^3 \Delta G_v + 4\pi r^2 \gamma$

$\gamma \rightarrow$ specific surface energy of the particle

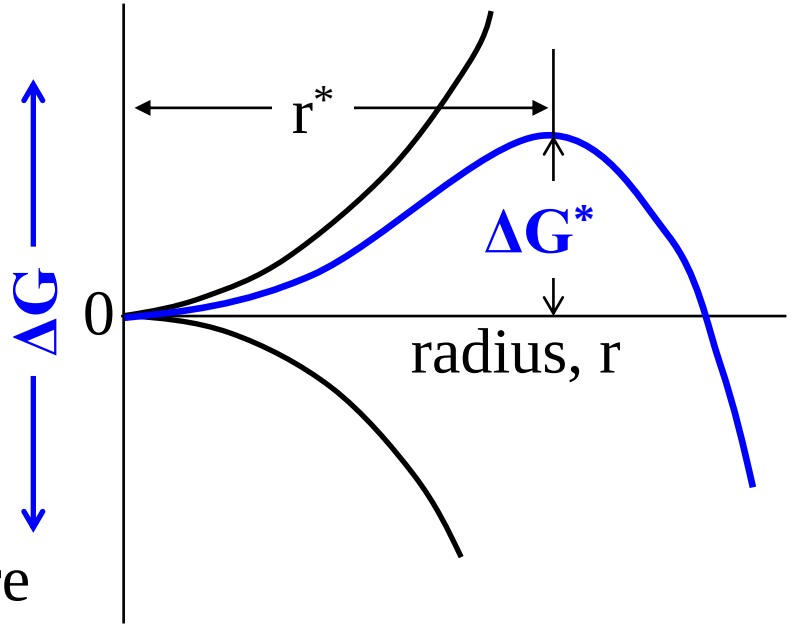
$d(\Delta G)/dr = 0$ when $r = r^*$

$$r^* = -2\gamma/\Delta G_v \qquad \Delta G^* = \frac{16\pi\gamma^3}{3(\Delta G_v)^2}$$

$$\Delta G_v = \frac{L(\Delta T)}{T_m} \qquad \Delta T = (T_m - T)$$

L – latent heat

T_m - equilibrium solidification temperature



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Solidification in welding

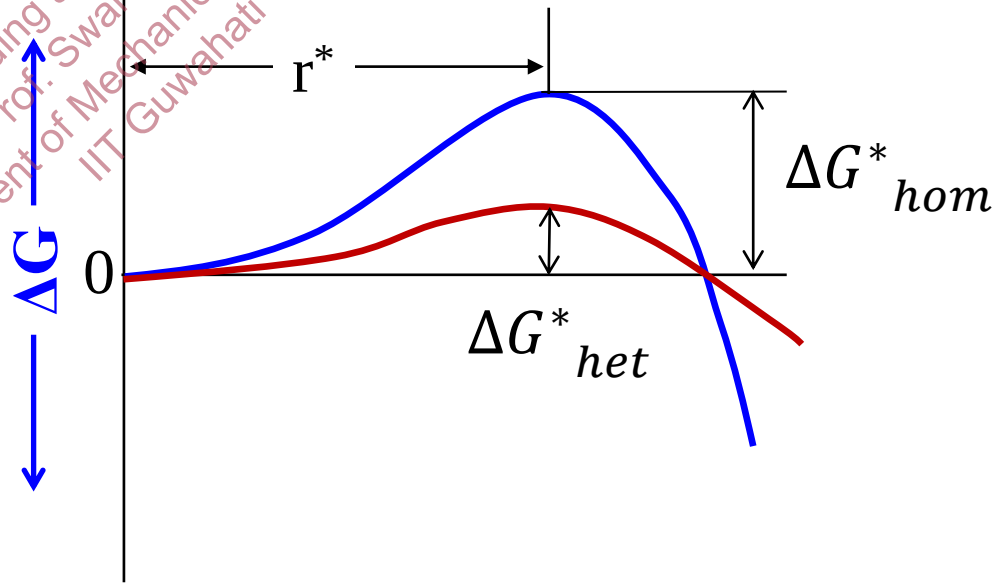
Heterogeneous Nucleation – Formation of a critically sized solid from the liquid on preexisting sites (surface or interface)

Energy barrier for heterogeneous nucleation is less

$$\Delta G^*_{het} = \Delta G^*_{hom}\, S(\theta)$$

$S(\theta)$ - shape of the nucleus

$0 < S(\theta) < 1$



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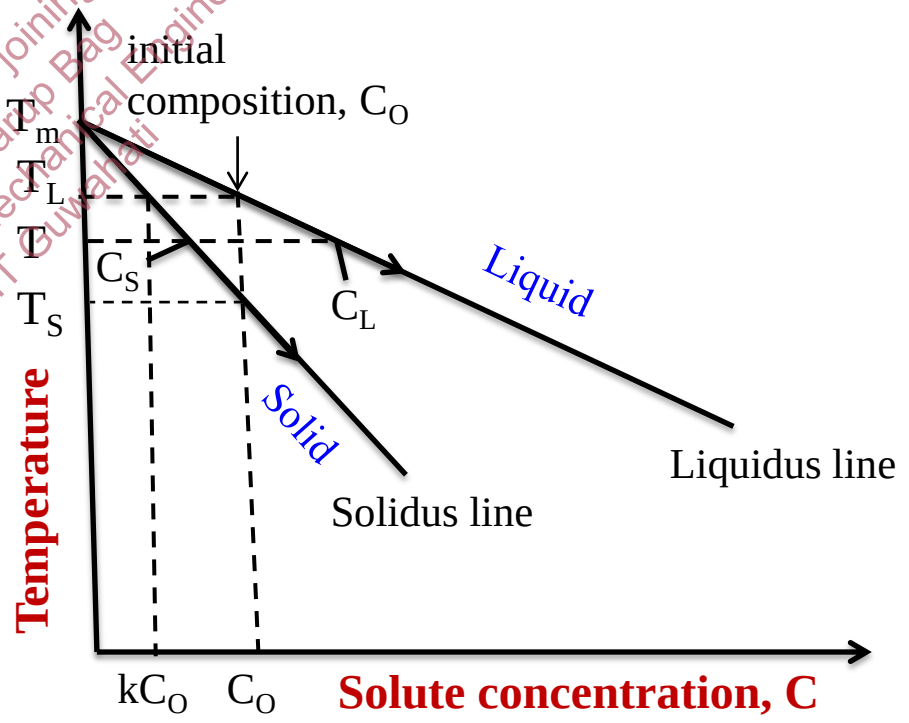
Solidification in welding

- ✓ Liquid of uniform composition - rarely uniform after solidification
- ✓ Solute atoms in the liquid - redistributed during solidification

Redistribution of the solute – depends on thermodynamics (phase diagram) and kinetics (diffusion, undercooling) and fluid flow



Binary phase diagram

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Solidification in welding

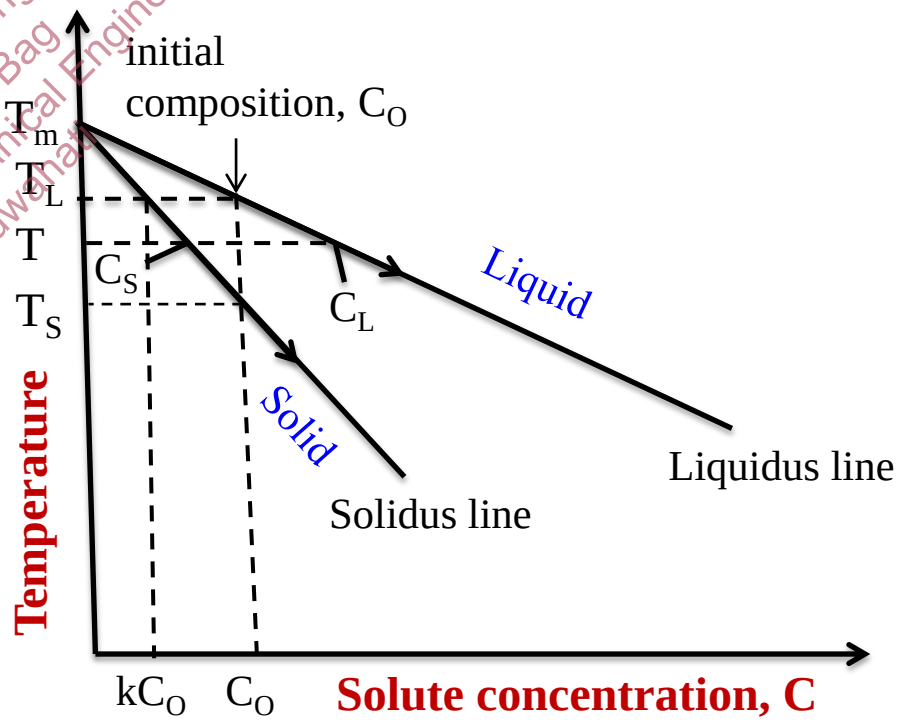
Phase diagram

- Assume initial composition C_O
- Solidification begins - when liquid cools to T_L
- At temperature T - C_S and C_L are the compositions of solid and liquid at the S/L

At equilibrium temperature (T)

Partition ratio or the equilibrium segregation coefficient

$$k = \frac{c_S}{c_L}$$



Binary phase diagram

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Solidification in welding

- ✓ The solute content of the liquid (C_L) continues to rise during solidification by lowering the solidification temperature
- ✓ As the solid grows from the liquid, its solute content (C_S) also continues to rise
- ✓ For k < 1, C_S and C_L both increases as temperature T of the S/L interface drops during the solidification
- ✓ The slope of the liquidus line, m_L, is less than zero when k < 1 and vice versa
- ✓ If a liquidus line is straight, a temperature T on the liquidus line can be expressed as

$$T = T_m + m_L C_L$$

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Solidification in welding

Complete diffusion in solid and liquid

- ✓ f_S and f_L - the fractions of solid and liquid
- ✓ Area $C_S f_S$ and $C_L f_L$ - amounts of solute in the solid and liquid
- ✓ Area $C_0(f_S + f_L)$ represents the amount of solute in the liquid before solidification

$$C_S f_S + C_L f_L = C_0(f_S + f_L) = C_0$$

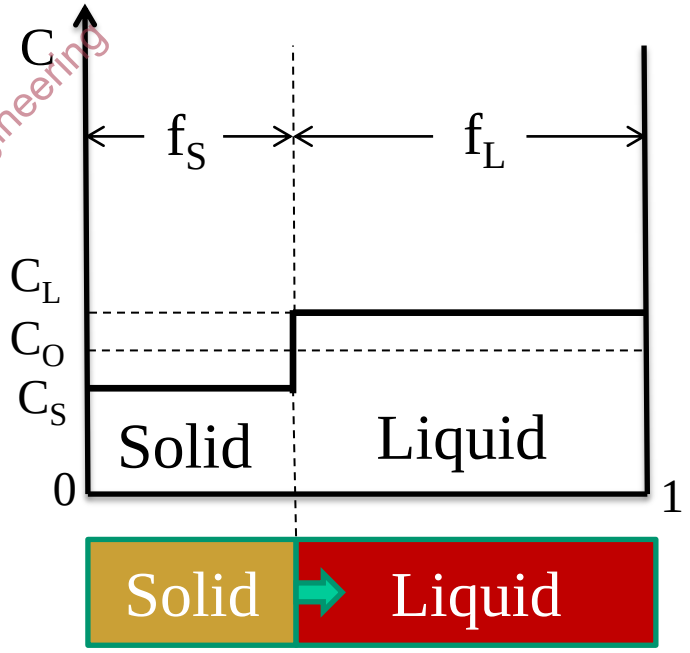
- ✓ Lever rule

$$f_L = \frac{C_0 - C_S}{C_L - C_S} \quad \text{and} \quad f_S = \frac{C_L - C_0}{C_L - C_S}$$

- ✓ Composition of liquid $C_L = \frac{C_0}{f_L + k(1 - f_L)}$

Conservation of solute

$f_S + f_L = 1$



Total volume of material

Equilibrium solidification

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Solidification in welding

Different types of grain structure

Equiaxed grains – crystals grow almost equally in all directions commonly found adjacent to a cold mold wall

Columnar grains – long and thin created under steep temperature gradient

- ✓ Solidification is relatively slow
- ✓ Grow perpendicular to the surface

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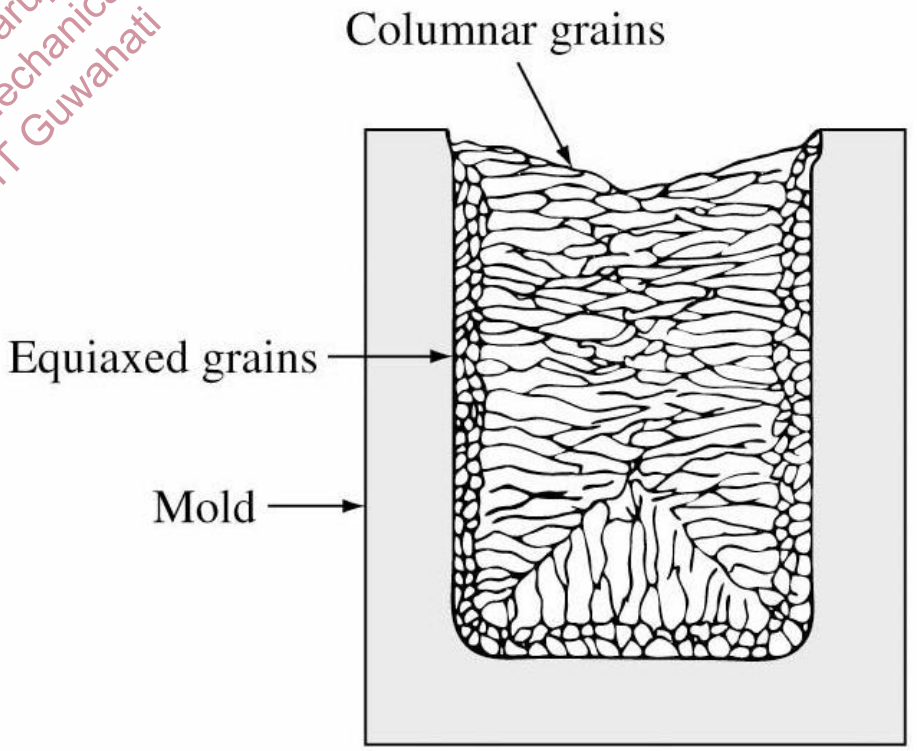

Solidification in welding

- ✓ No solid diffusion and complete diffusion in liquid
- ✓ No solid diffusion and limited liquid diffusion

Solidification Modes

- During the solidification of a pure metal the S/L interface is usually planar

- For an alloy, the mode of solidification in the S/L interface can be

  planar, cellular, or dendritic depending on the solidification condition and material system involved

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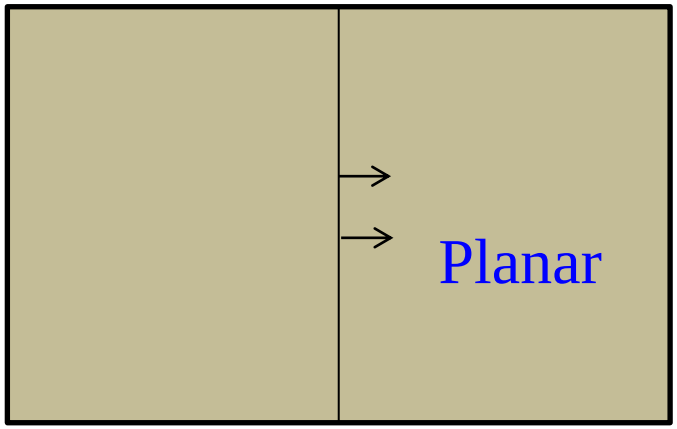
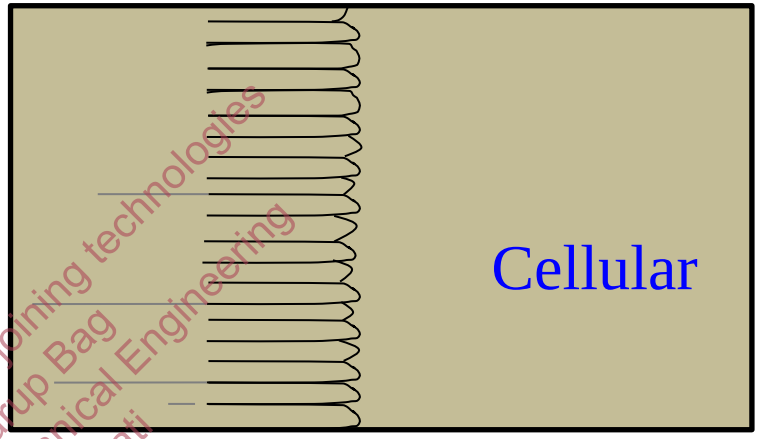
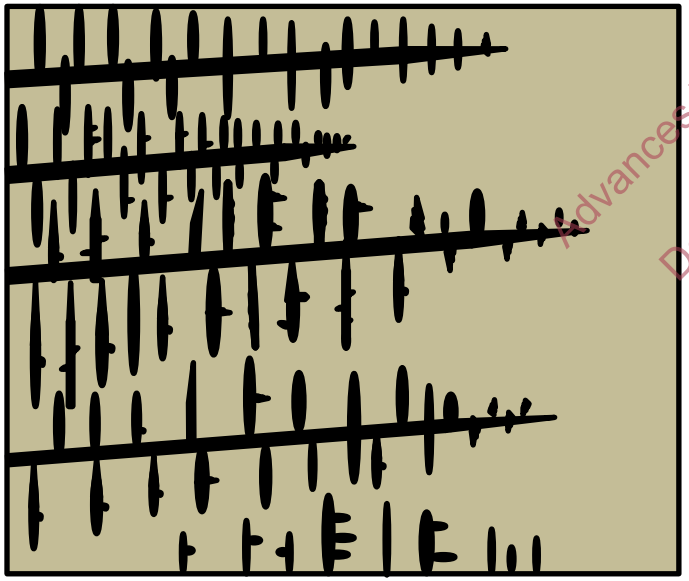
Solidification in welding

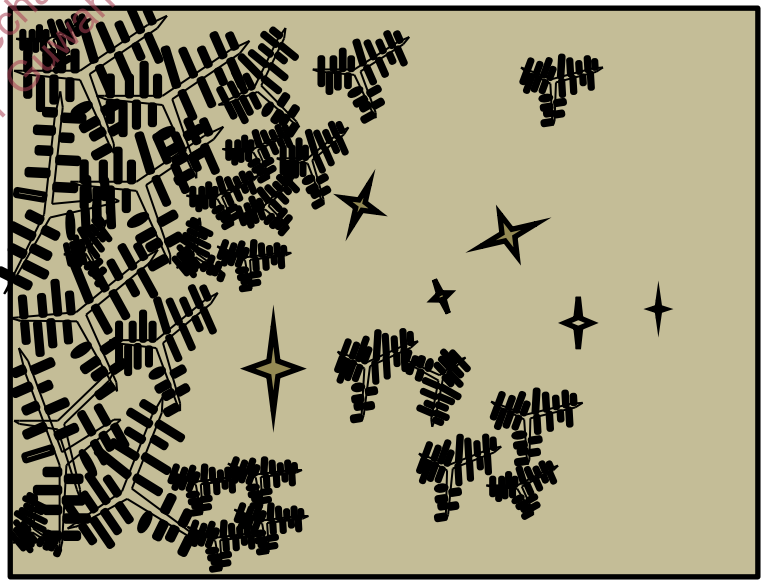
Basic solidification modes







Columnar dendritic



Equiaxed dendritic

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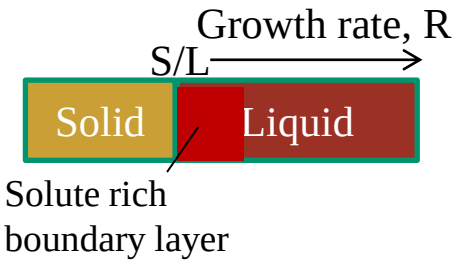
Solidification in welding

Constitutional Supercooling: It occurs during solidification - due to compositional solid changes - results in cooling a liquid below the freezing point ahead of the S/L interface

Quantitatively describes the breakdown of a planar S/L interface during solidification

Consider the solidification of alloy C_0 at the steady state with a planar S/L interface

D_L - diffusion coefficient of the solute in the liquid (L^2/T), R - growth rate (L/T), G – temperature gradient (θ/L)



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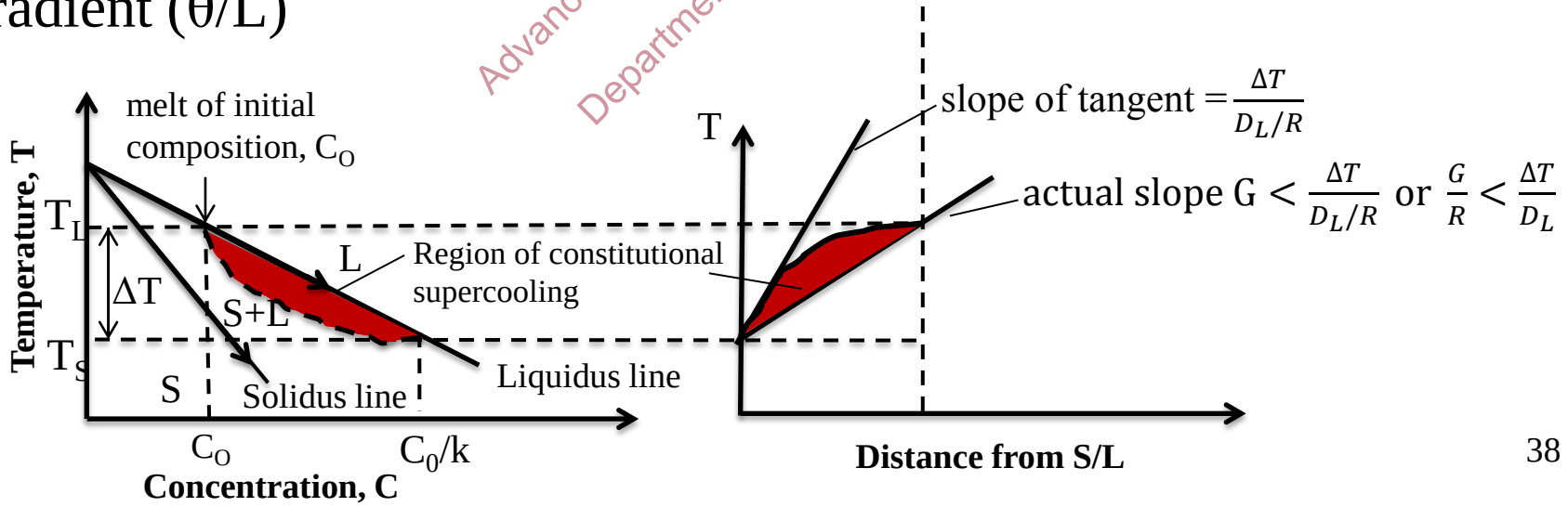

Solidification in welding

- ✓ Shaded area is the region of constitutional supercooling, where liquid alone is unstable and solid - liquid coexist
- ✓ The thickness of the boundary layer at the steady state = D_L/R
- ✓ To avoid constitutional supercooling: $\frac{G}{R} \geq \frac{\Delta T}{D_L}$
- ✓ For a planar S/L interface to be stable at the steady state $\frac{G}{R} \geq \frac{\Delta T}{D_L}$
- ✓ Planar S/L interface may break down to a cellular or dendritic one so that solid cells or dendrites can coexist with the intercellular or interdendritic liquid
- ✓ Higher G and lower R, leads to a stable planar S/L interface
- ✓ Higher ΔT and D_L – leads to more difficulty for a planar S/L interface to be stable

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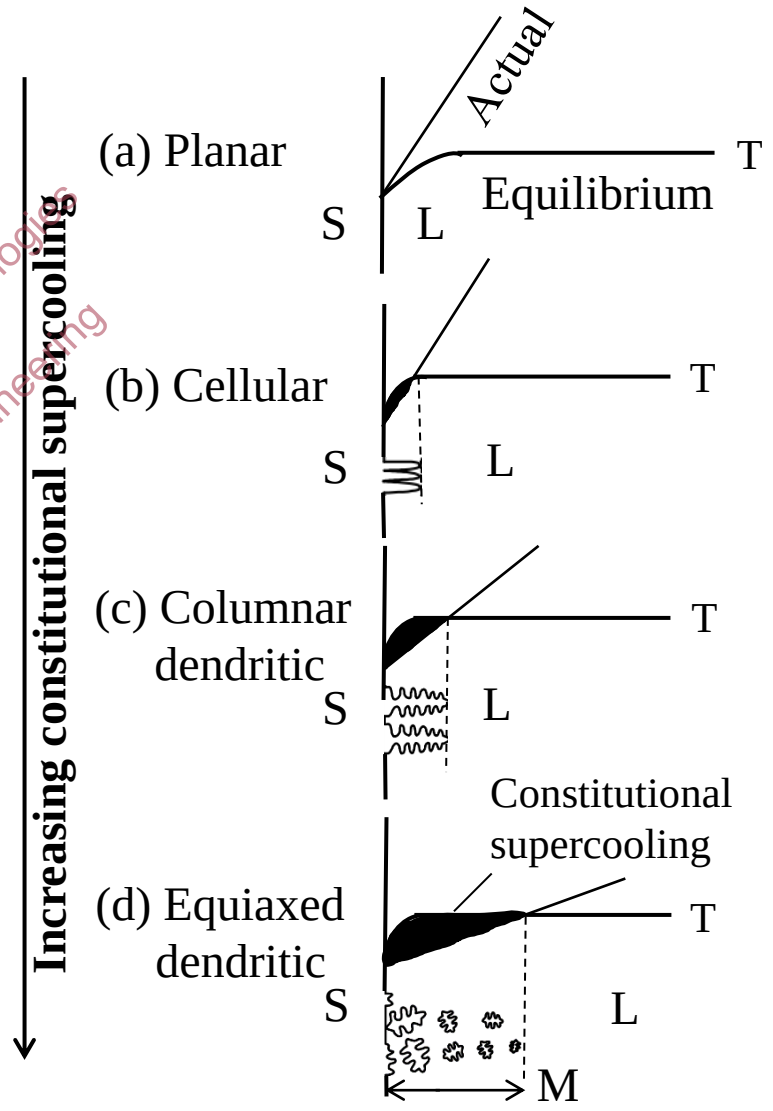
Solidification in welding

Solidification mode

Planar - cellular – columnar dendritic - equiaxed dendritic

- ✓ The region where dendrites and the liquid phase coexist is called the mushy zone
- ✓ At very high degree of constitutional supercooling, the mushy zone becomes wide - which will promote the equiaxed dendrites to nucleate



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Solidification in welding

Effect of cooling rate

Temperature gradient G and the growth rate R affects the solidification microstructure

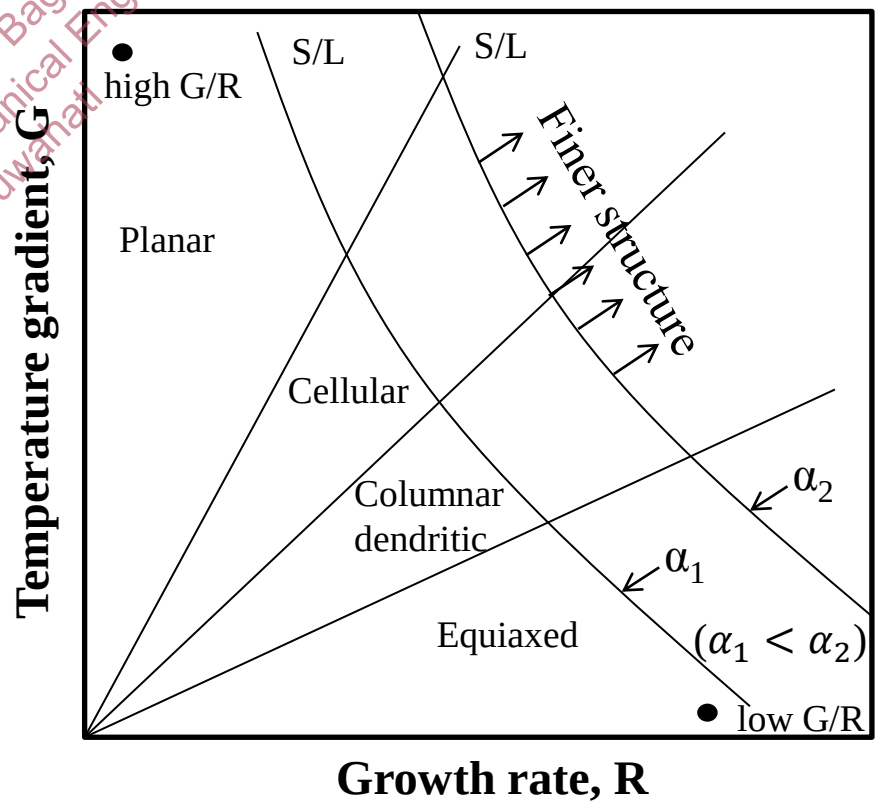
Product of G.R is also known as cooling rate (α)

The ratio G/R determines the mode of solidification

G.R (θ/T) governs the size of the solidification structure

Greater G.R - finer the solidified cellular or dendritic structure

Higher cooling rate - Fine structure; Lower cooling rate - Coarser structure



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Weld Microstructure

Grain structure affects the susceptibility to solidification cracking and mechanical properties

Epitaxial growth at fusion boundary (autogenous fusion welding)

- ✓ Molten metal is in contact with the base material
- ✓ Grain growth initiates at the solid liquid interface and proceeds towards the weld centre
- ✓ Called as epitaxial nucleation and growth
  - ➢ For FCC or BCC crystal structure material, the trunks of columnar dendrites grow in the <100> direction.

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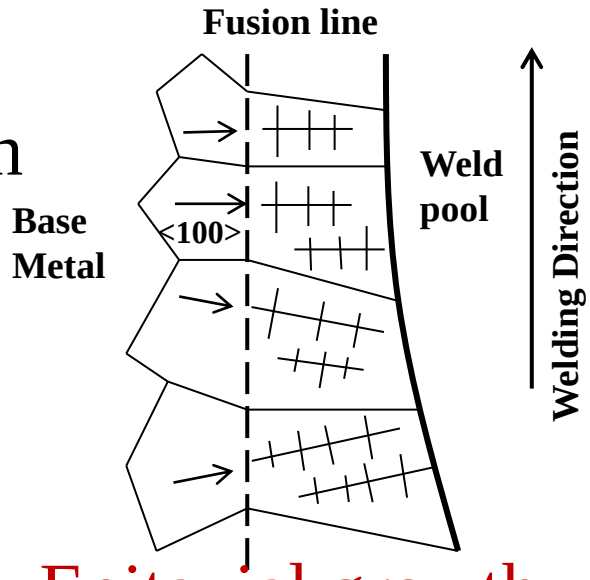

Epitaxial growth

Weld Microstructure

- ✓ Using filler metal - weld metal composition may differs that leads to different crystal structure for weld and base metal
- ✓ Epitaxial growth is no longer possible for welding with a filler material and new grains nucleates at the fusion boundary
- ✓ During solidification grains tend to grow perpendicular to weld pool boundary - because of maximum temperature gradient
- ✓ Columnar dendrites or cells within each grain tend to grow in the easy-growth direction

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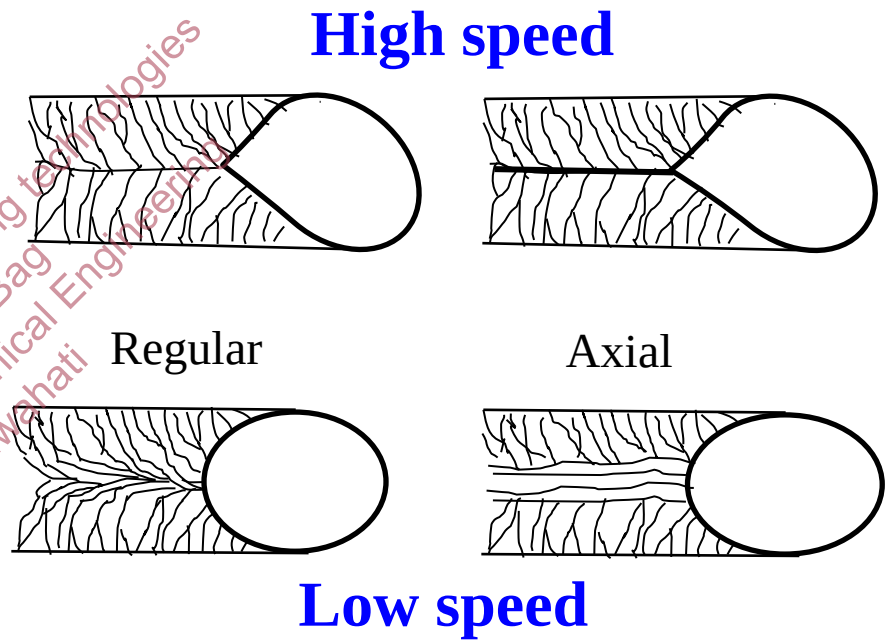
Crystal Structure	Easy-Growth Direction	Materials
Face-centered-cubic (fcc)	<100>	Aluminum alloys, austenitic stainless steels
Body-centered-cubic (bcc)	<100>	Carbon steels, ferritic stainless steels
Hexagonal-close-packed (hcp)	$< 10\bar{1}0 >$	Titanium, magnesium
Body-centered-tetragonal (bct)	<110>	Tin

Weld Microstructure

Effect of welding parameters on grain structure

- ✓ High welding speed - Elongated weld pool
- ✓ Low welding speed - Elliptical weld pool



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- ➢ Trailing pool boundary of teardrop shape - weld pool is nearly straight
- ➢ Columnar grains are straight normal to pool boundary

Effect on columnar-grain structure

- ➢ Trailing boundary of elliptical shape – weld pool is curved
- ➢ Columnar grains are curved in order to grow perpendicular to the pool boundary

Weld Microstructure

Weld metal nucleation mechanisms

Mechanism of nucleation - controls microstructure of the weld pool

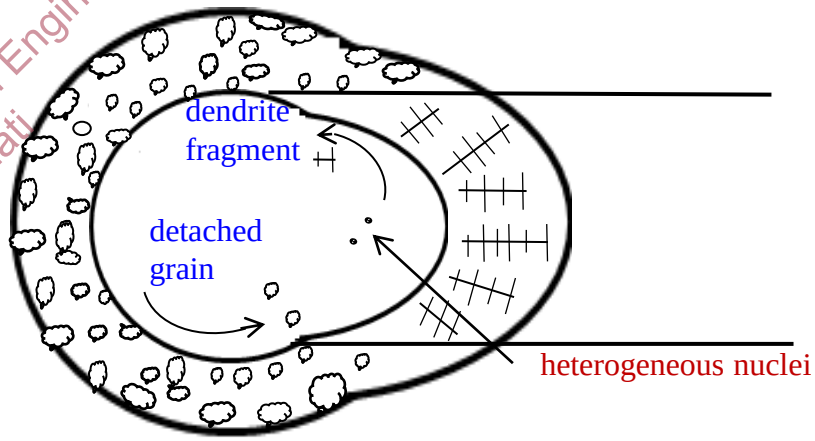
- Growth of columnar grains - interrupted by the formation of new grains
- With new grains - growth of epitaxial grains interrupted

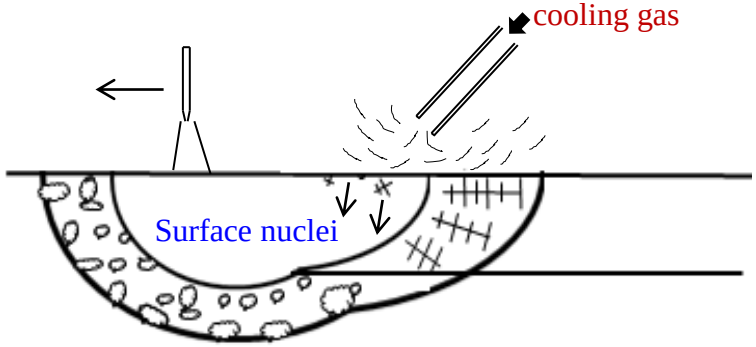
✓ New grains are often equiaxed rather than columnar

Dendrites - seen in the mushy zone, behind the trailing portion

Mechanism for nucleation of new grains

- Dendrite Fragmentation
- Grain Detachment
- Heterogeneous Nucleation





Ref: Kou, S., and Le, Y., Welding Journal, 65:305s, 1986.

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Weld Microstructure

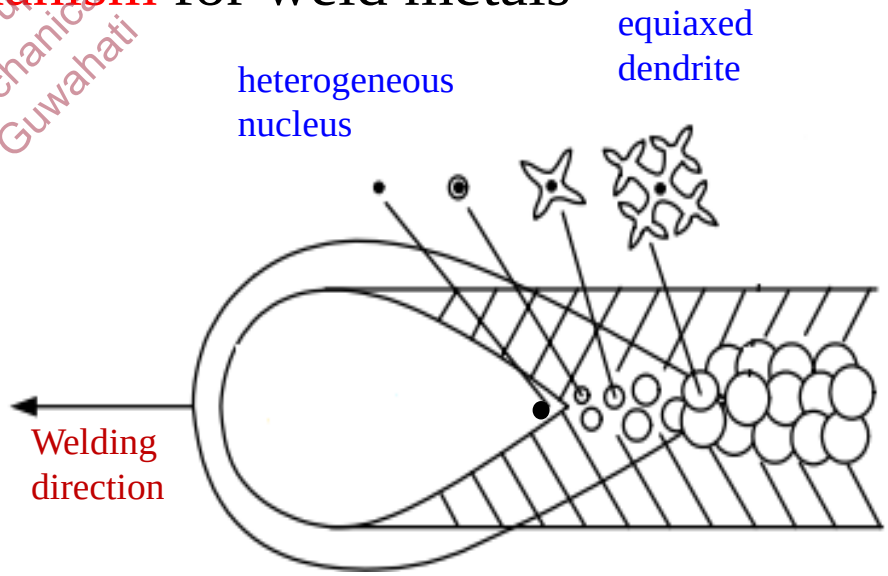
Dendrite Fragmentation

- Weld pool convection is the principle cause of fragmentation of dendrite tips in the mushy zone
- Dendrite fragments are carried into the bulk weld pool and act as nuclei for new grain.
- Known as the grain refining mechanism for weld metals

Grain Detachment

- Weld pool convection cause partially melted grains to detach from the solid–liquid mixture

- They can act as nuclei for the formation of new grains



Ref: S. Kou, Welding Metallurgy, 2nd Ed., Wiley, 2013.

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Weld Microstructure

Heterogeneous Nucleation

- If the liquid metal contain foreign particles in the weld pool, then the critical energy barrier for nucleation reduces significantly

Effect of welding parameters on heterogeneous nucleation

- ✓ Formation of equiaxed grains is enhanced by higher heat inputs and welding speeds
- ✓ With the increase in heat input and the welding speed, the temperature gradient (G) at the end of the weld pool is reduces
- ✓ With increase in the welding speed, the solidification rate of the weld metal (R) also increases
- ✓ The ratio G/R should be decreased and the constitutional supercooling in front of the advancing solid–liquid interface should be increased for equiaxed grain formation

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Weld Microstructure

Control on Grain structure

Weld metal microstructure significantly affect mechanical properties

- ✓ The weld metal tensile strength increases as the amount of equiaxed grains increases.
- ✓ Fine equiaxed grains reduces the susceptibility of the weld metal to solidification cracking during welding.
- ✓ Fine grains improves the ductility and fracture toughness in the case of steels and stainless steel weld

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to obtain fine grain in the weld fusion zone, different such processes are

Inoculation

Weld pool stirring, Arc oscillation, and Arc pulsation

Stimulated Surface Nucleation

Phase Transformation

1. Equilibrium phase diagram (Binary alloy system)
2. Time-temperature-transformation (TTT) diagram
   - Isothermal transformation diagram (not most practical)
3. Continuous cooling transformation (CCT) diagram
   - Most heat treatment follows

Weld zone is subjected to variable cooling rate

1. Melt zone – solidification
2. HAZ – solid state phase transformation

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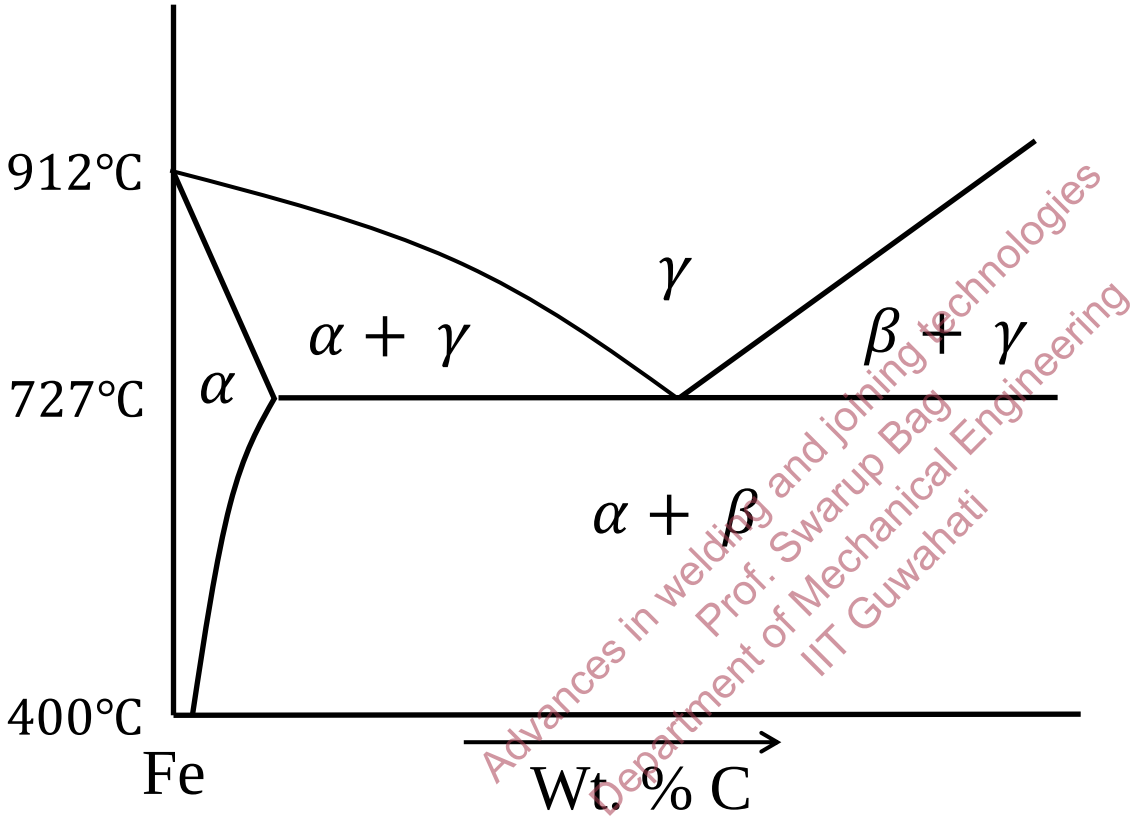
Phase Transformation



γ – Austenite

α – Ferrite

β – Cementite

δ – Ferrite

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Iron-iron carbide phase diagram

Phase Transformation

- ✓ Weld microstructure of SS 310 (high Ni) - consists of primary austenite dendrites and interdendritic δ ferrite between the primary and secondary dendrite arms
- ✓ Weld microstructure of SS 309 (high Cr) - consists of primary lathy δ ferrite in an austenite matrix
- ✓ Solid redistribution during solidification is reduced at high cooling rate for low Cr: Ni ratio.
- ✓ High Cr : Ni ratio alloys solidify as δ ferrite as the primary phase, and their ferrite content increase with increasing cooling rate because the δ→γ transformation has less time to occur at high cooling rate

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Phase Transformation

Weld microstructure in low-carbon steels

- As austenite γ is cooled down from high temperature, α-ferrite nucleates at the grain boundary and grow inward as Widmanstätten pattern
- At lower temperature, it is too slow for Widmanstätten ferrite to grow to the grain interior, instead acicular ferrite nucleates from inclusions

Grain boundary ferrite, Polygonal ferrite, Widmanstätten ferrite, Acicular ferrite, Upper bainite, Lower bainite

Different cooling rate (CCT Diagram) – for 4340 type steel
Martensite, Bainite, Ferrite, Pearlite

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Solidification Cracking

Cracks occur during welding for the following reasons

- ✓ Temperature gradient causes thermal strain
- ✓ Compatibility of various phases due variation in composition
- ✓ Embrittlement of grain boundaries
- ✓ Volumetric contract during cooling

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Solidification Cracking

Mainly two types of cracks

Hot crack – Occurs at elevated temperatures (Solidification cracking)

Cold crack – Occurs after solidification (Hydrogen cracking)

General measure to prevent cracking

- ✓ Minimize stresses from the shrinkage during cooling – change the design
- ✓ Trials with parameters and sequence of welding
- ✓ Preheating of the components to be welded
- ✓ Following slow or moderate cooling rate by avoiding rapid cooling rate

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Solidification Cracking

Hot cracking (Solidification cracking)

- ✓ Low ductility material
- ✓ Wide range of solidification temperature
- ✓ Presence of impurity elements (low melting point) like sulfur, phosphorus and boron
- ✓ Impurity segregation mainly at weld centerline – creates shrinkage stress

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Prevented by

- ➢ Low level of C, S, P, B
- ➢ High level of Mn

Solidification Cracking – Laser welding

Decreasing the welding heat input - one of the most effective way to prevent hot cracking

Laser welding - is a solution for lower welding heat input

Hot cracking susceptibility - enhanced in laser welding of stainless steels and nickel base alloys

- keyhole type high depth of penetration (typical shape)
- rapid cooling with an extremely low heat input

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Solidification Cracking – Laser welding

Mechanism of solidification cracking

- ✓ Thermal strain exceeds the critical value
- ✓ Strain curve intersect with solidification brittleness temperature range (BTR)

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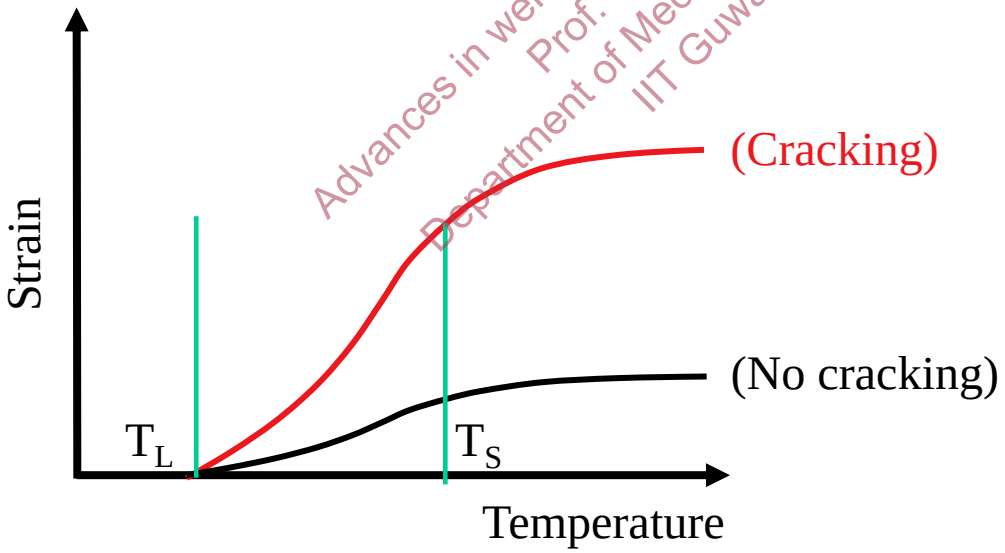

Heat Treatment of weld joint

Importance of heat treatment

- Phase transformations during heating
- Effect of cooling rate on structural changes
- Effect of carbon content and alloying elements

- ✓ The fast cooling rates associated with welding often produce martensite
- ✓ During postweld heat treatment, martensite is tempered (transforms to ferrite and carbides)
  - – Reduces hardness, Reduces strength
  - – Increases ductility, Increases toughness
- ✓ Residual stress is also reduced by the postweld heat treatment

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Summary

- Using of proper shielding gas is important for fusion welding
- Residual stress and distortion is mainly influenced by solidification shrinkage, thermal contraction, metallurgical changes and boundary constraints
- Temperature gradient (G) and the growth rate (R) affects the solidified microstructure
- Postweld heat treatment is required often to temper the martensitic structure
- Presence of low melting point impurity enhances the susceptibility of solidification cracking

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Thank you
for your kind attention

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End of Module 6

Welding Metallurgy