Welding Metallurgy

Module 3

Module 3 – Welding Metallurgy

- 3A – Basics of Metallurgy Principles
- 3B – Basics of Welding Metallurgy
- 3C – Carbon and Low Alloy Steels
- 3D – Stainless Steels
- 3E – Nickel-base Alloys
- 3F – Other Nonferrous Alloys
- 3G – Polymers

Module 3 Learning Objectives

- Describe basic metallurgical principles including strengthening mechanisms
- Describe the basic concepts of welding metallurgy, microstructure influences on properties and weldability
- Understanding different types of carbon and low alloy steels, stainless steels, nickel alloys including microstructure development and weldability issues of each alloy system
- Understanding the effect of preheat, PWHT and temper bead welding on carbon and low alloy steels
- General understanding aluminum, titanium, and copper alloys characteristics including welding metallurgy and weldability issues
- General understanding and properties of polymers and methods of joining

Basics of Metallurgy Principles

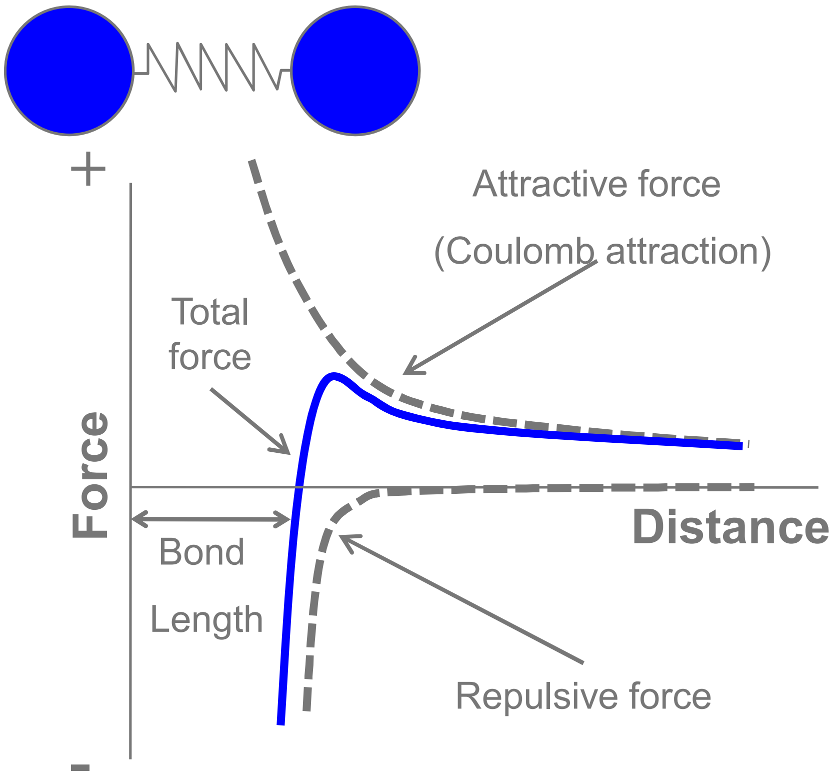
Module 3A

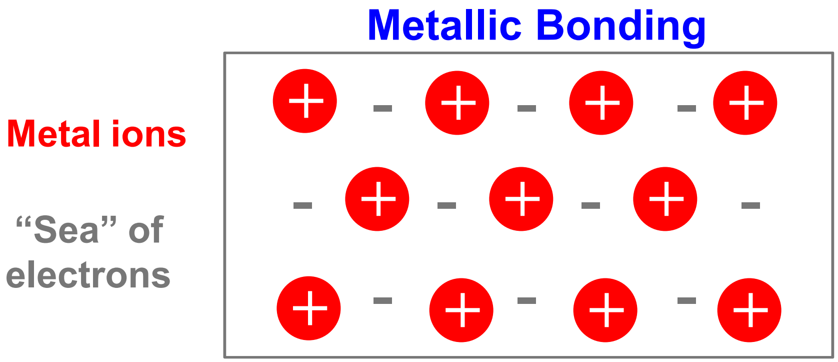
Types of Atomic Bonds

- Primary Bonds (strong bonds)
  - Ionic (table salt: NaCl)
  - Covalent (ceramics and glasses)
  - Metallic (metals and alloys)
    - Easy movement of electrons leads to high conductivity
    - Lack of bonding directionality leads to high atomic packing
- Secondary Bonds (weak bonds)
  - Van der Waals (dipole interactions)
  - Hydrogen bonding

Metallic Bonding

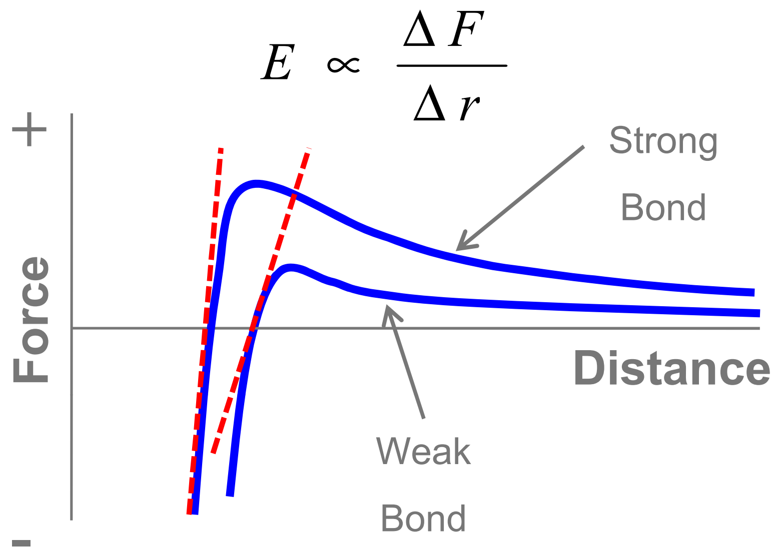
- Metal stiffness is proportional to the bonding strength
- Metallic bonds behave as though they were attached with a spring
- Bringing the atoms close increases the repulsion and attraction



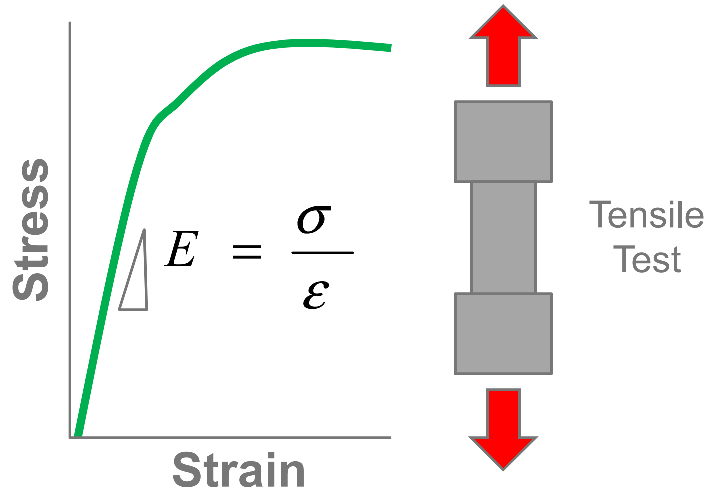

Metallic Bonding

Elastic Modulus

- Elastic behavior of metals means that bonds are stretching (but not breaking)
- Metal stiffness is proportional to the bonding strength
- The linear behavior of bonds near the equilibrium bond length results in the linear elastic region of a stress strain curve
- Such behavior is observed during tensile testing



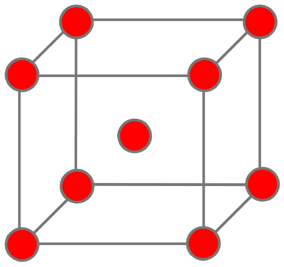
$$E \propto \frac{\Delta F}{\Delta r}$$

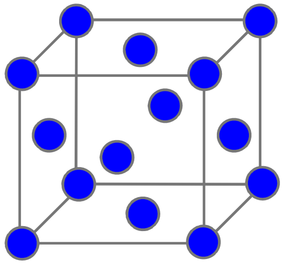


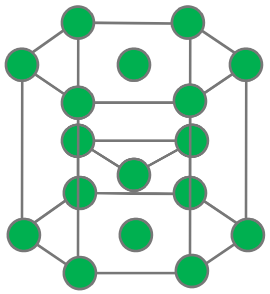
$$E = \frac{\sigma}{\varepsilon}$$

Crystal Structure

- Atoms arrange themselves into different structures
- Body-centered cubic (BCC) structure
    - Iron
    - Ferritic steels
- Face-centered cubic (FCC) structure
    - Nickel (and its alloys)
    - Aluminum (and its alloys)
- Hexagonal close-packed (HCP) structure
    - Titanium (room temperature)
    - Magnesium
    - Zirconium





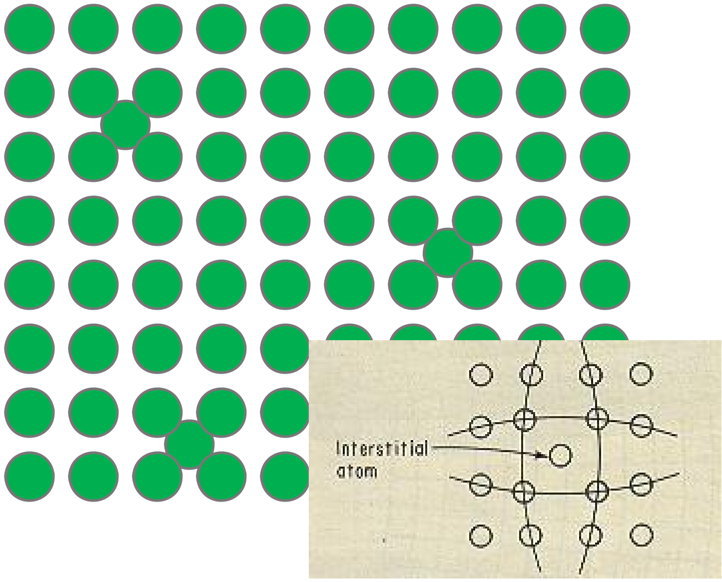


Defects in Metal Crystals

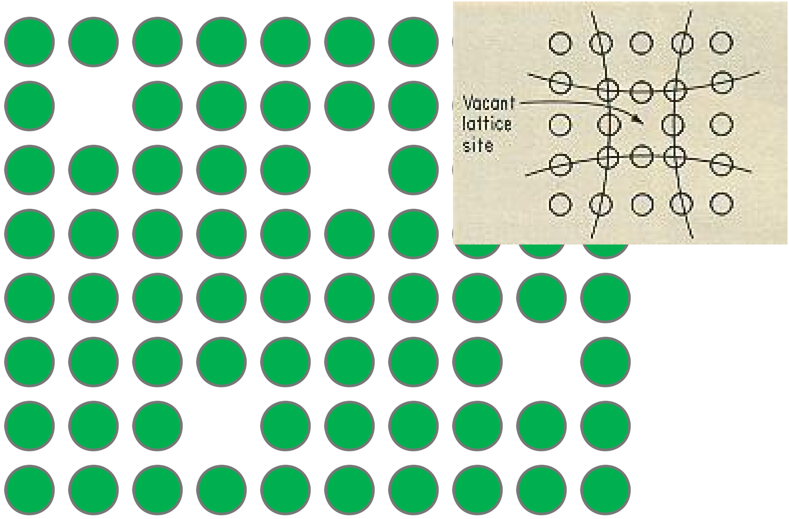
- Defects within a crystal structure can change the chemical and physical properties
- Some of the important defects are as follows:
- Point defects (0-Dimensions)
  - Vacancies
  - Solid Solutions
- Line defects (1-Dimensional)
  - Dislocations
- Planar defects (2-Dimensional)
  - Grain boundaries
  - Surfaces

Point Defects

Self-interstitial defects



Vacancy defects



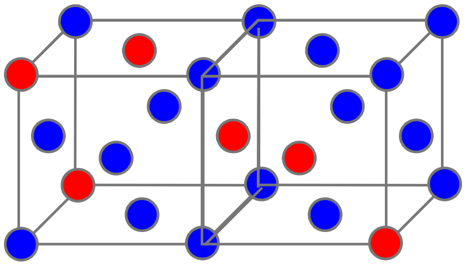
- Metals will always contain these two types of defects
- The number of vacancies is temperature dependent (important for diffusion)

Equilibrium number of vacancies

$$N_V = N \exp\left(-\frac{Q_V}{kT} \right)$$

Solid Solutions

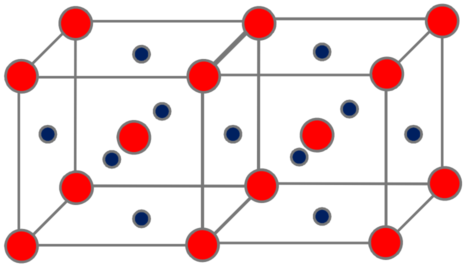
- Metal alloys contain at least two or more elements
- Even “pure” metals typically contain some impurities
- Two types of metal solutions:
  - Substitutional solutions contain a solvent and solute where the solute occupies lattice sites of the solvent



● Ni is the solvent
● Cu is the solute

Cu and Ni both have the FCC crystal structure.

  - Interstitial solutions contain a solute that occupies non-lattice sites



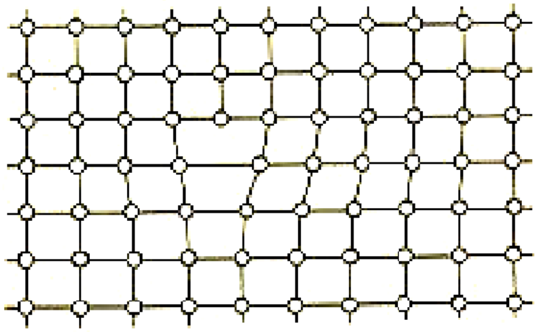
● Fe is the solvent
• C is the solute

Fe has the BCC structure and C occupies interstitial sites. This is a common arrangement in steels.

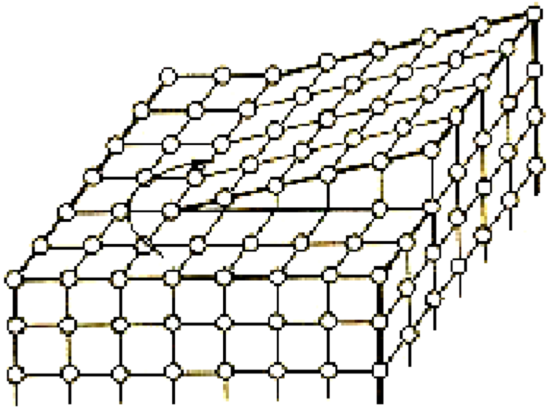
Line Defects

- Line defects are known as dislocations
- Movement of dislocations through a material results in plastic deformation
- Edge and screw dislocations are both found in metals

Edge dislocation

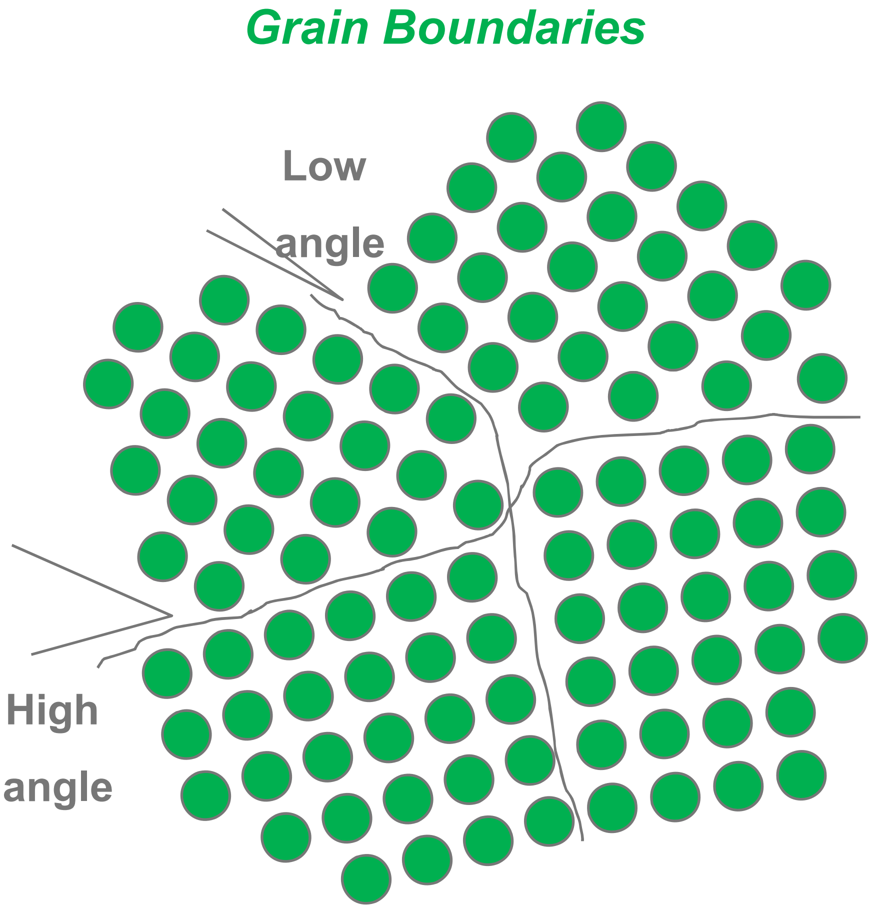


Screw dislocation



Planar Defects

- Each unique crystal of atoms has a surface
- Metals typically contain multiple crystals which have their own orientation
- Each crystal is referred to as a grain
- The region between two different grains is called a grain boundary
  - Low angle boundaries
  - High angle boundaries

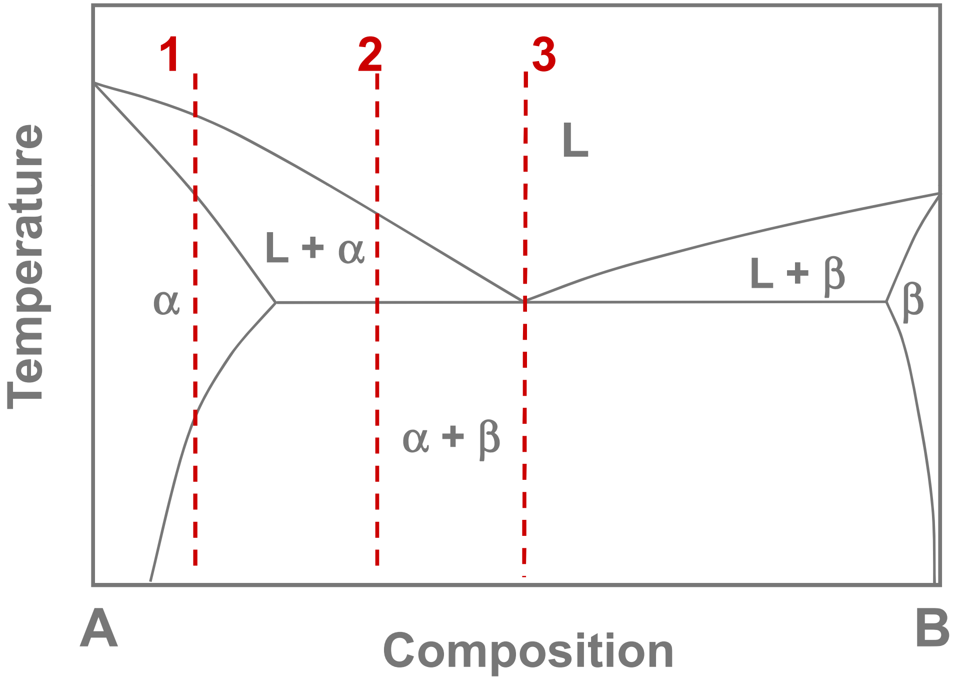


Phase Diagrams

- A phase is a homogenous system with uniform physical and chemical properties (i.e., crystal structures)
- Metals and alloys may have different phases
- Composition and temperature are used to predict the phases (crystal structure) present in an alloy
- Reactions occur at equilibrium (infinite time)
- Common phase diagram types include:
  - Complete solid solution (isomorphous)
  - Eutectic
  - Peritectic
  - Eutectoid
- The Lever Rule is used to determine the phase balance and composition of constituents
- Microstructure evolution during slow (equilibrium) cooling

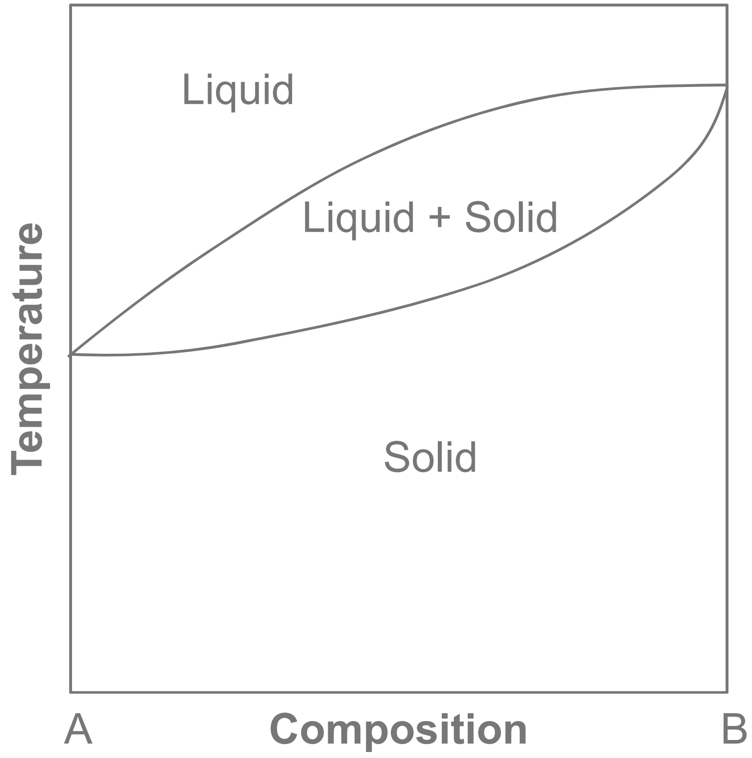
What is a Phase Diagram?

- Describes structure of materials based on temperature and composition
- Assumes constant pressure
- Features
  - Liquidus
  - Solidus
  - Solvus
- Phase transformations
  - Composition 1
  - L → L + α → α → α + β
  - Composition 2
  - L → L + α → α + β
  - Composition 3
  - L → α + β

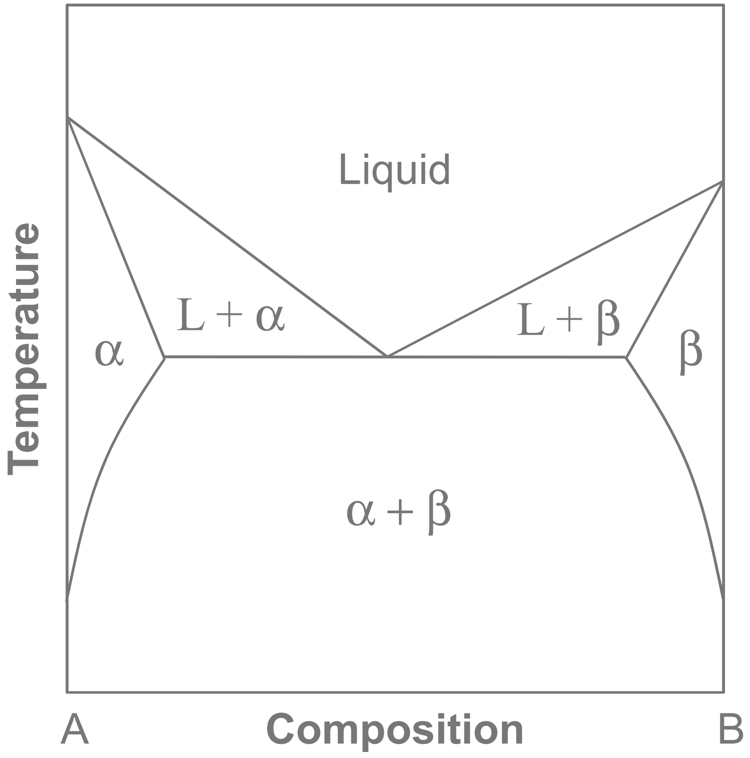


Phase Diagrams

Isomorphous



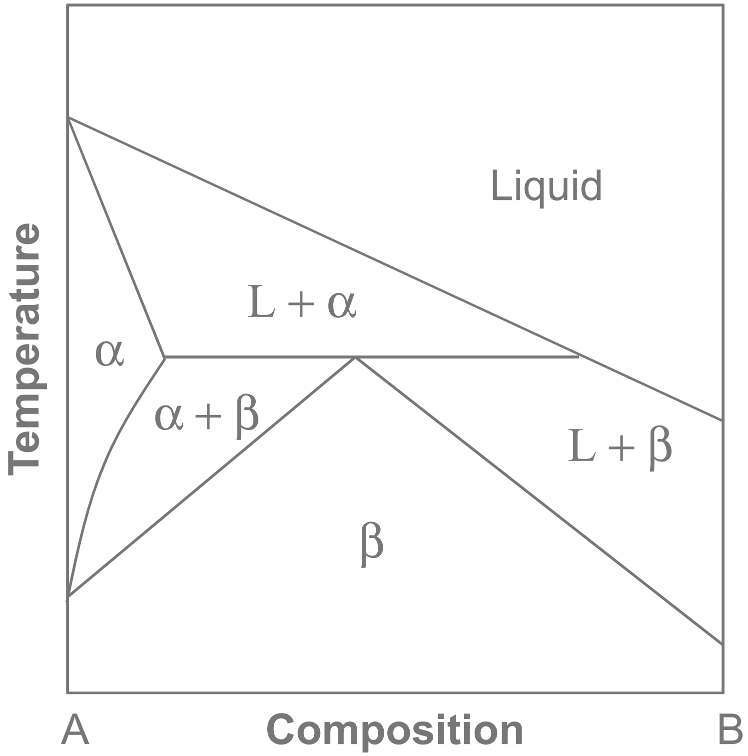
Eutectic



Phase Diagrams

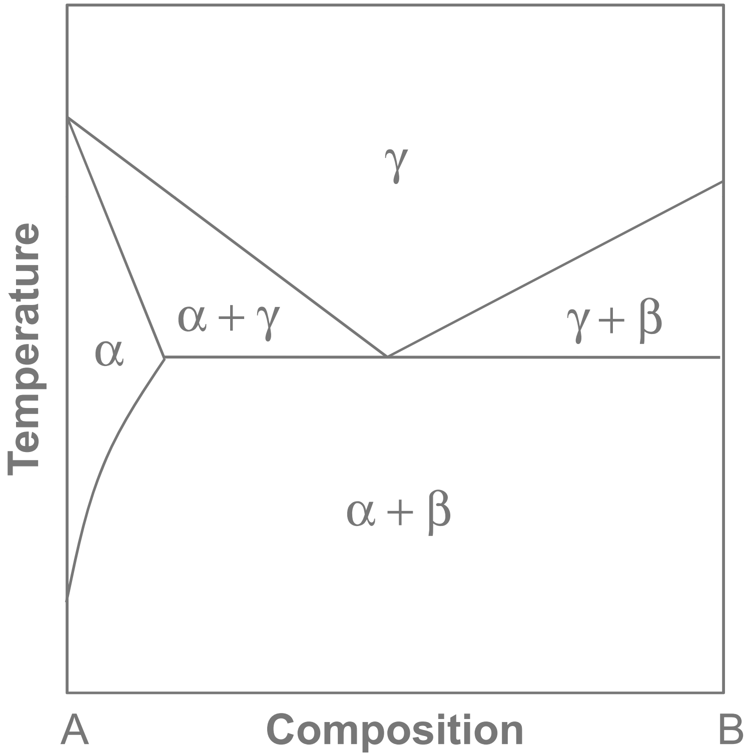
Peritectic

$L + \alpha \rightarrow \beta$



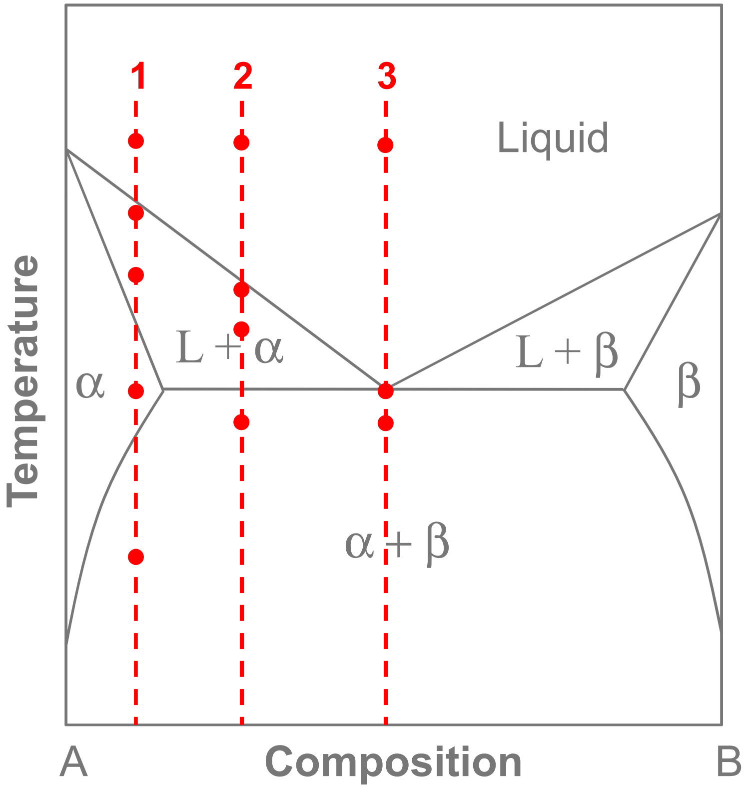
Eutectoid

$\gamma \rightarrow \alpha + \beta$

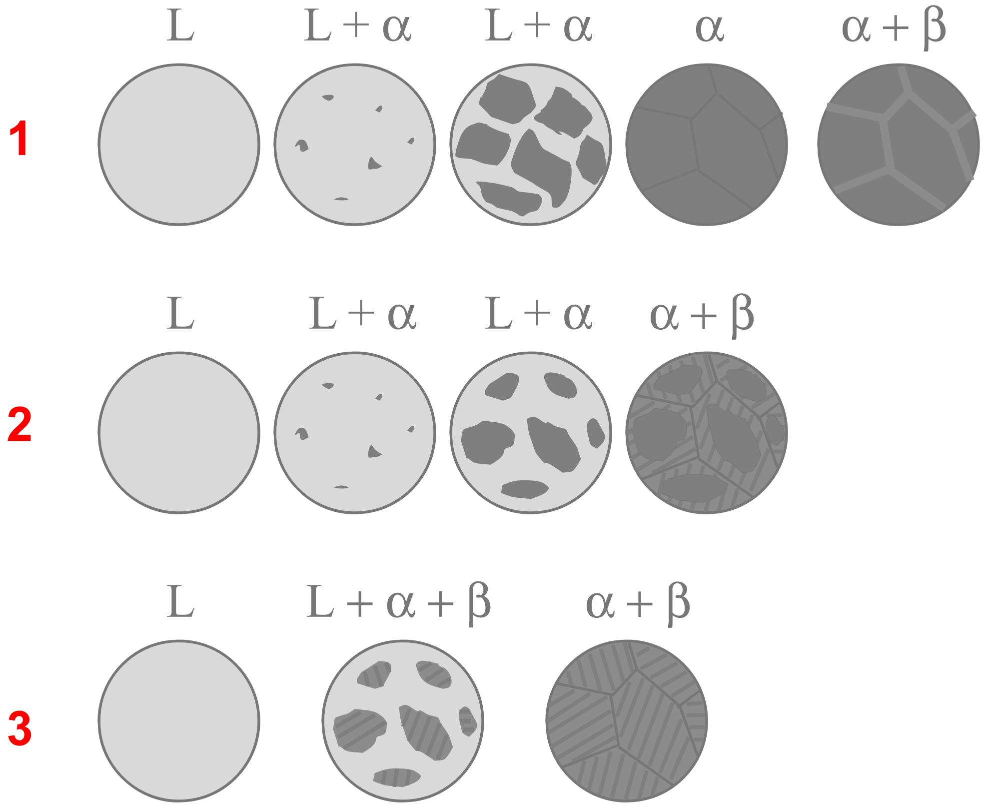


Microstructure Evolution During Slow Cooling

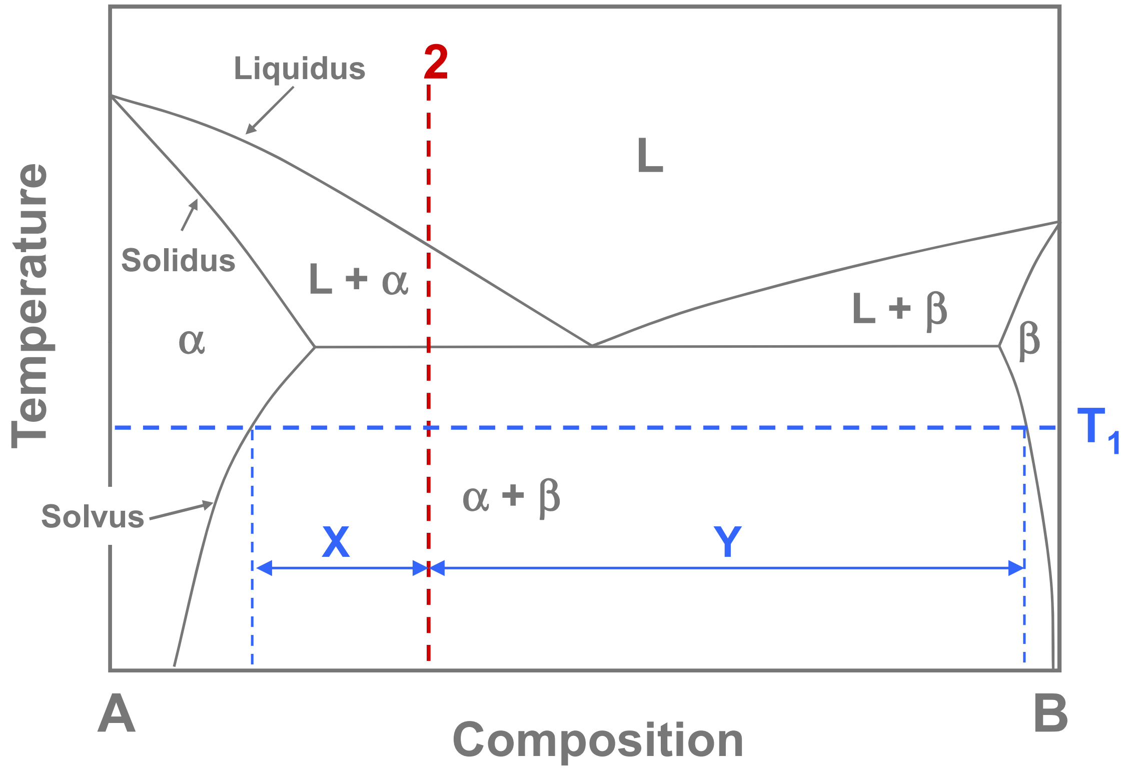
Eutectic System



Microstructure for Three Different Compositions

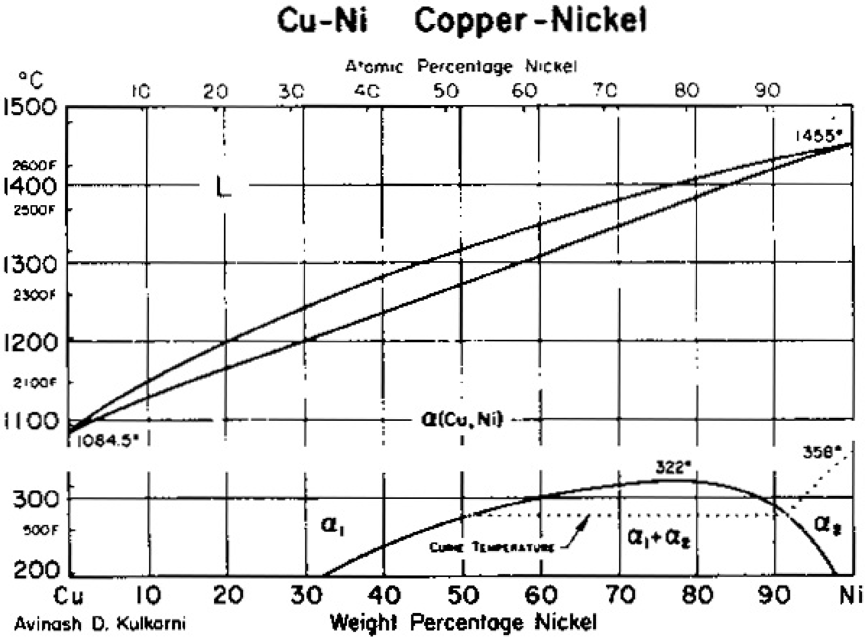


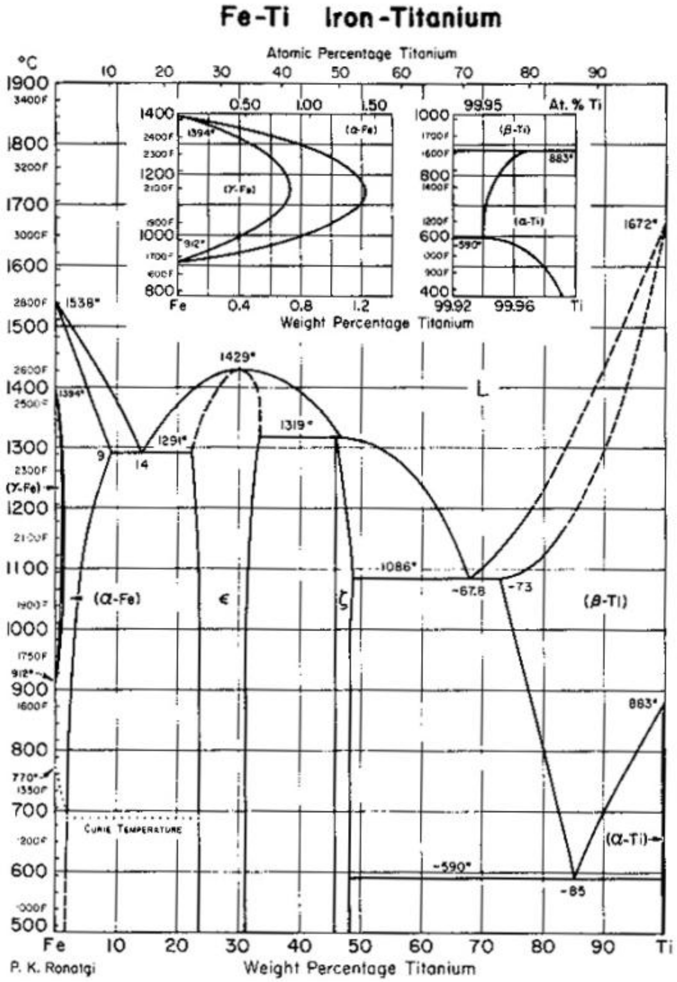
Determining Phase Balance



- The Lever Rule
  - Determines the percentage of phases present at a given temperature
  - At temperature T_1, Composition 2 is a mixture of α + β
- Percent α = $\frac{Y}{X + Y}$
- Percent β = $\frac{X}{X + Y}$

Some Examples of Phase Diagrams

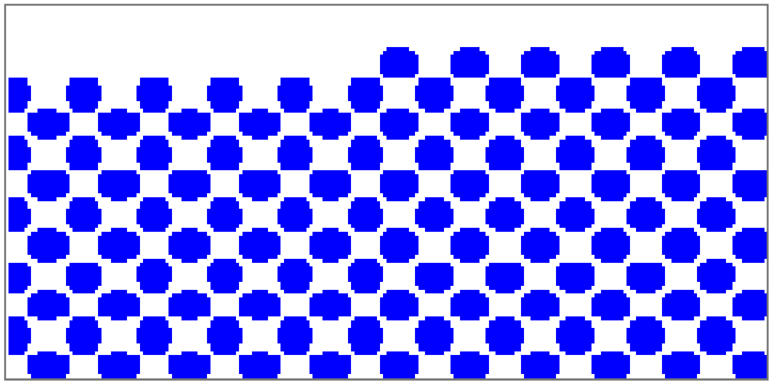




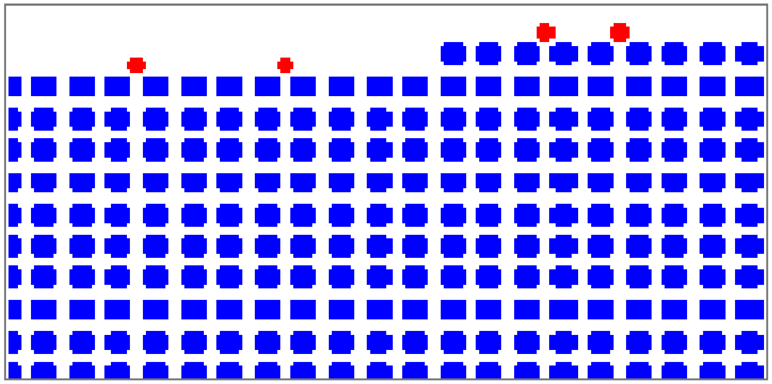
Diffusion

- Diffusion Mechanisms
  - Vacancy diffusion
  - Interstitial diffusion

Vacancy Diffusion



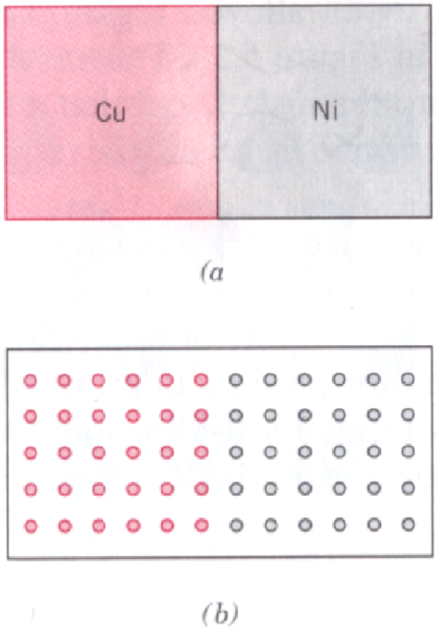
Interstitial Diffusion

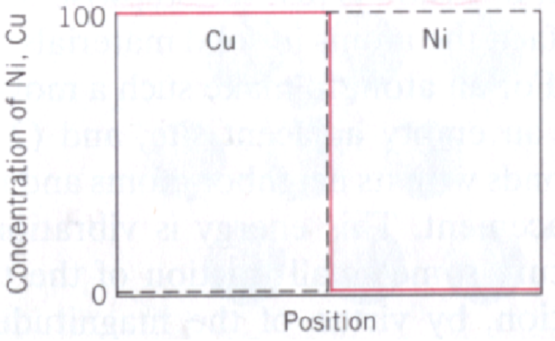


Reference: Defects in Crystals. Prof. Helmut Föll, University of Kiel, Germany.

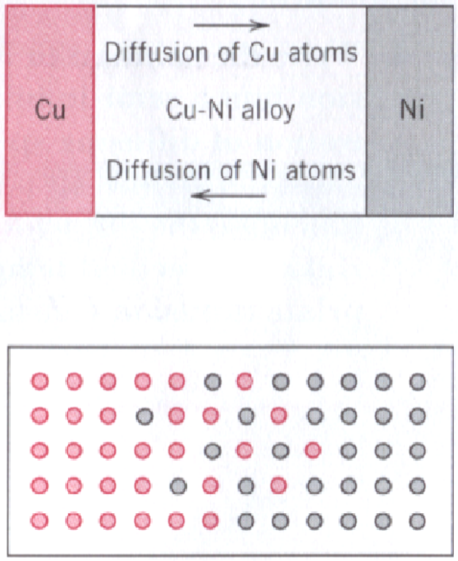
Interdiffusion of Two Metals

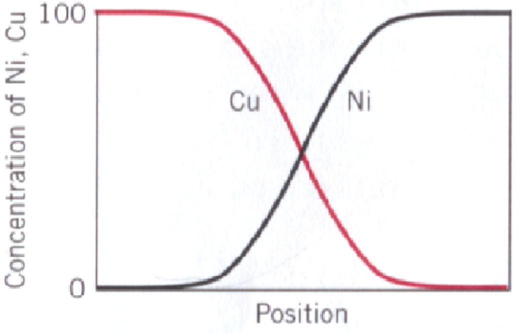
Before Heat Treatment At High Temperature





After Heat Treatment At High Temperature





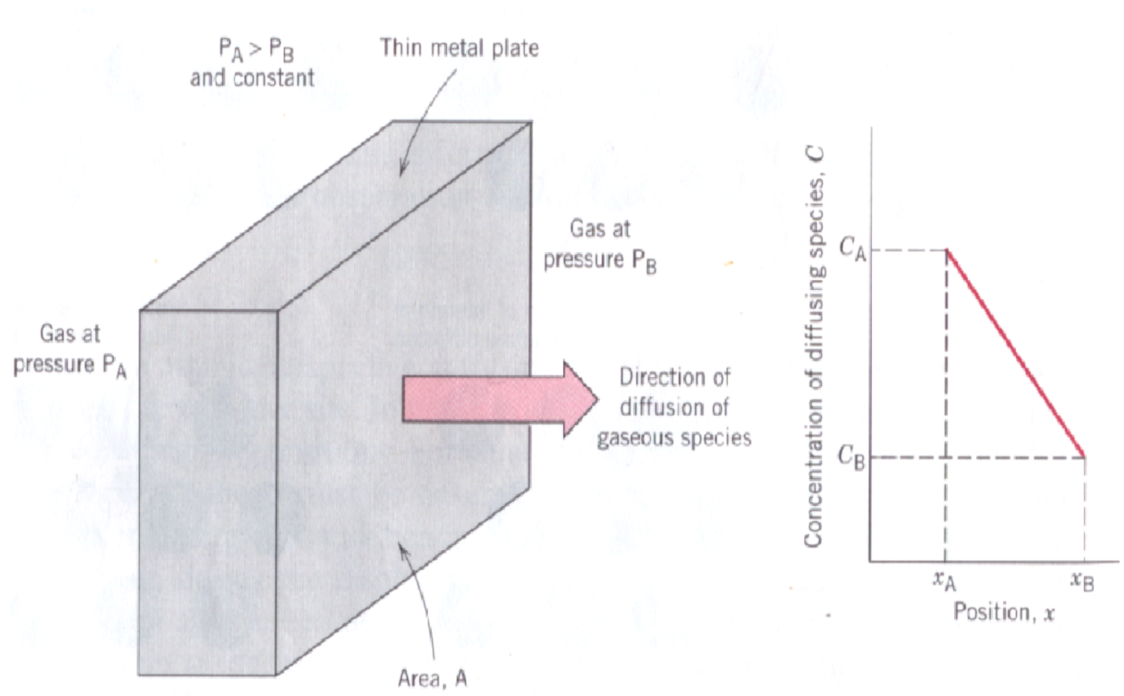
Fick’s First Law of Diffusion

- Flux is the mass diffusing through a fixed area per unit of time
- Diffusion flux (J) does not change with time during stead-state diffusion

Fick’s First Law:

$$J = -D\frac{dC}{dx}$$

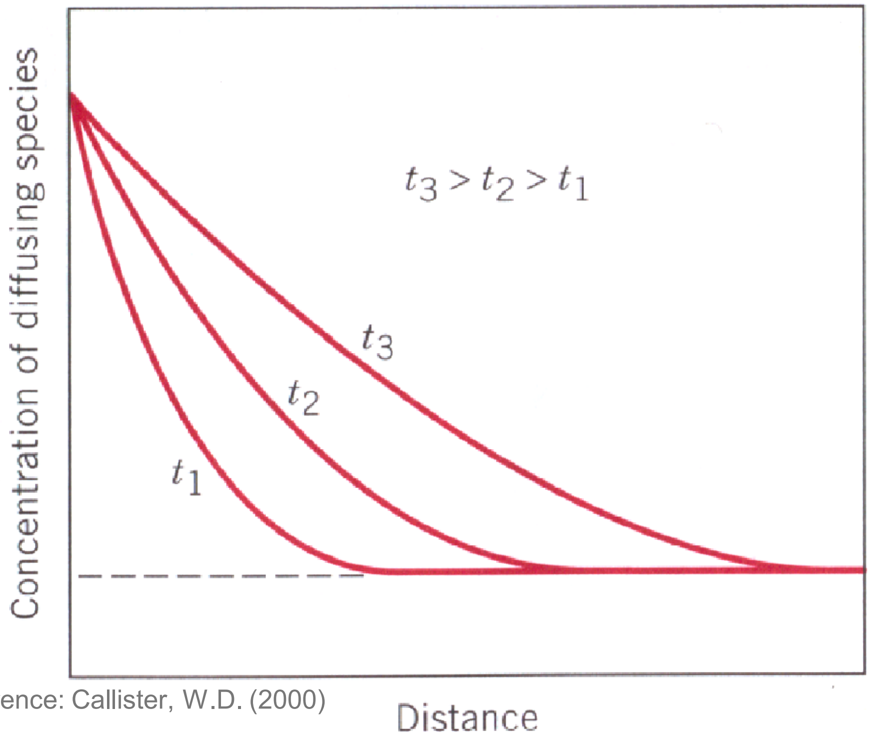
J, diffusion flux $(g/m^2 s)$
D, diffusion coefficient (m^2/s)
C, concentration (g/m^3)
x, position (m)



Reference: Callister, W.D. (2000)

Fick's Second Law of Diffusion

- Diffusion flux and the composition gradient typically vary with time
- This results in concentration profiles such as the one shown
- Fick's second law describes transient diffusion



Reference: Callister, W.D. (2000)

Fick's Second Law:

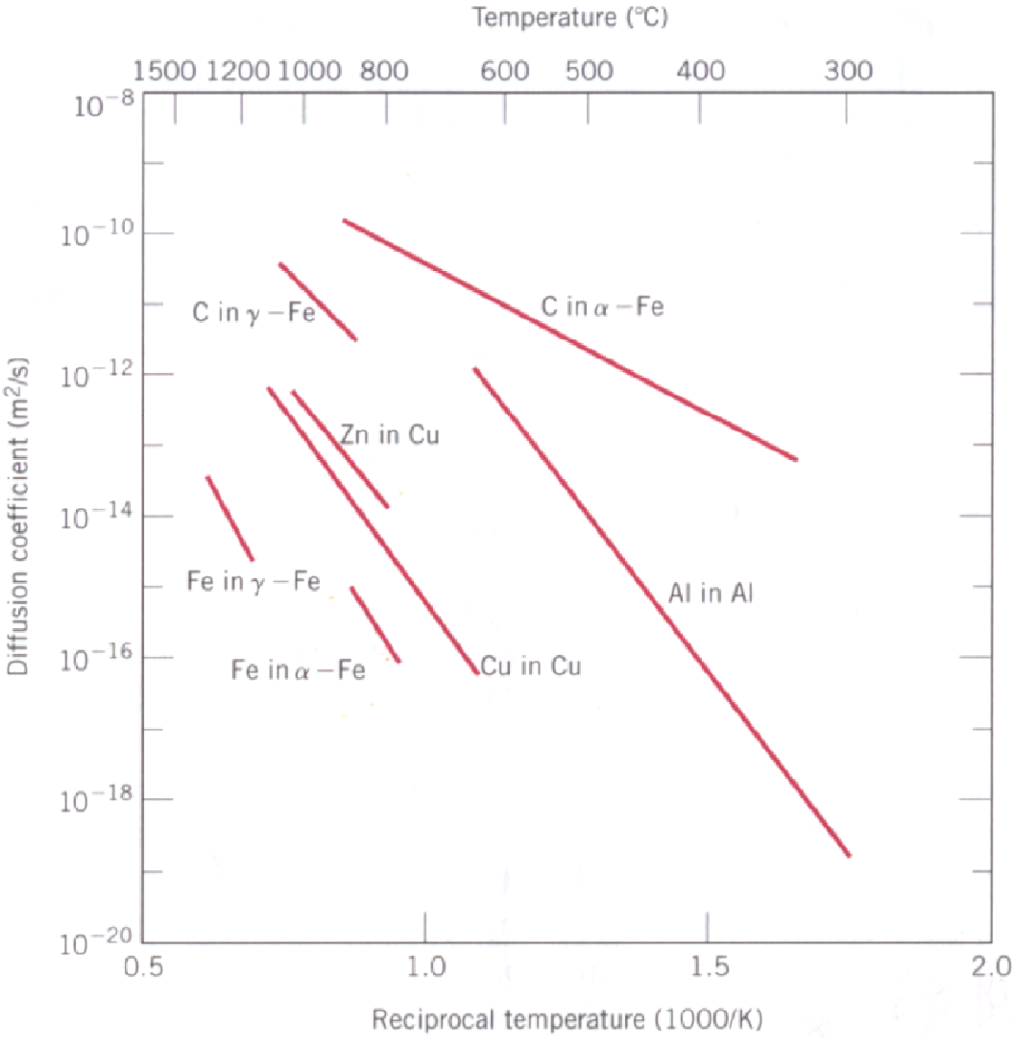
$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

t, time (s)
D, diffusion coefficient (m^2/s)
C, concentration (g/m^3)
x, position (m)

Diffusion Coefficients

- Temperature has a strong influence on diffusion coefficients
- This temperature dependence takes on the following form

$$D = D_0 \exp\left(-\frac{Q_d}{RT}\right)$$



Reference: Callister, W.D. (2000)

Strengthening Mechanisms of Metals

- Grain Size Reduction
- Solid Solution Strengthening
  - Interstitial
  - Substitutional
- Strain Hardening (cold work)
- Precipitation

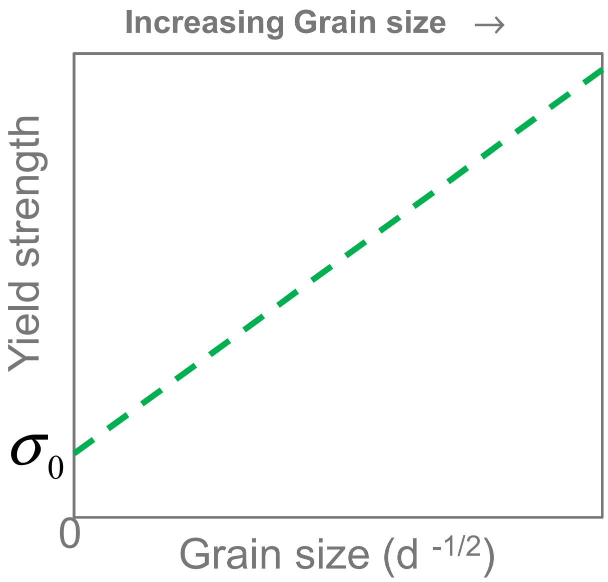
Importance of Grain Size

- Reducing grain size acts as a barrier to dislocation motion increasing strength and toughness
  - The dislocation must change directions when reaching a grain boundary since adjacent crystals have different crystal orientations
  - Slip of atomic planes is not continuous across the boundary

Yield strength varies with grain size according to the Hall-Petch equation

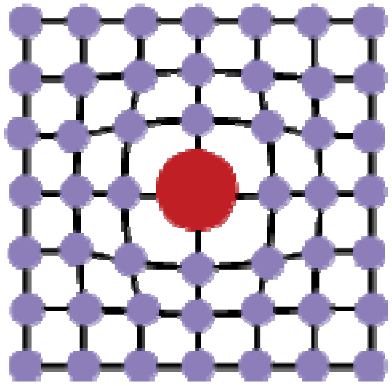
$$\sigma_Y = \sigma_0 + kd^{-1/2}$$

σ_Y, *yield strength*
σ_o, *k, material constants*
d, average grain diameter

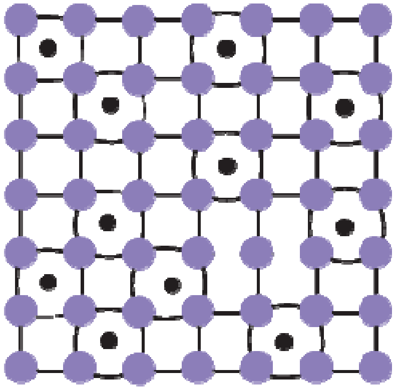


Solid-Solution Strengthening

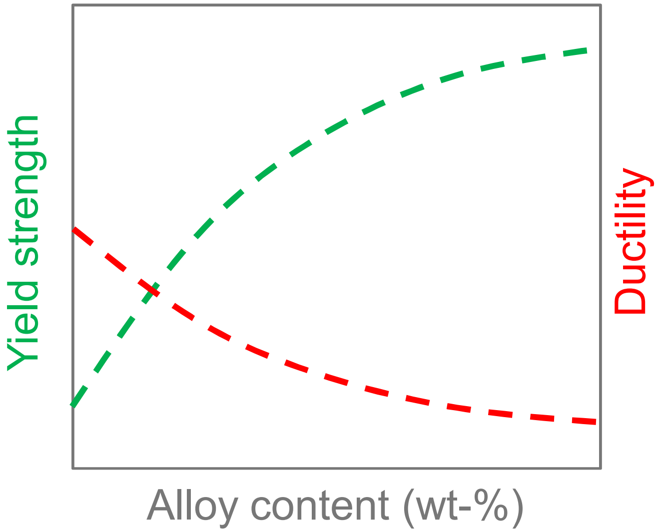
- Intentional alloying with impurity atoms exerts strains on the lattice surrounding the impurity



Substitutional Alloying



Interstitial Alloying

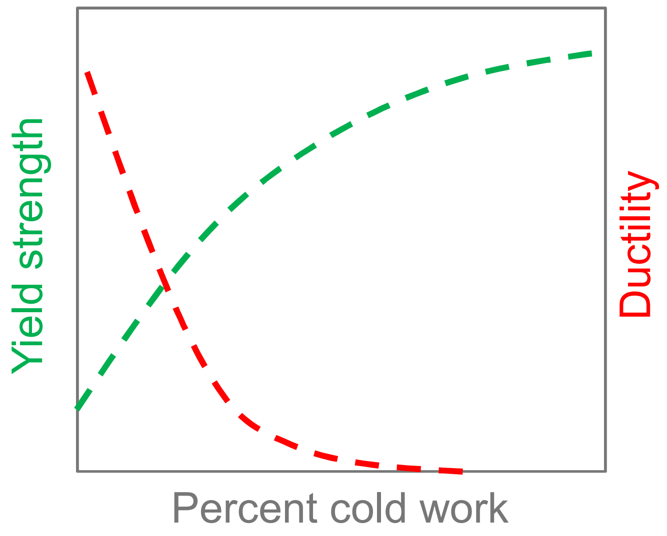


Increasing the alloying content results in an increase in yield strength

Strain Hardening

- “Cold work” or “work hardening” is done by plastically deforming a ductile metal at or near room temperature

Increasing the cold work results in an increase in yield strength

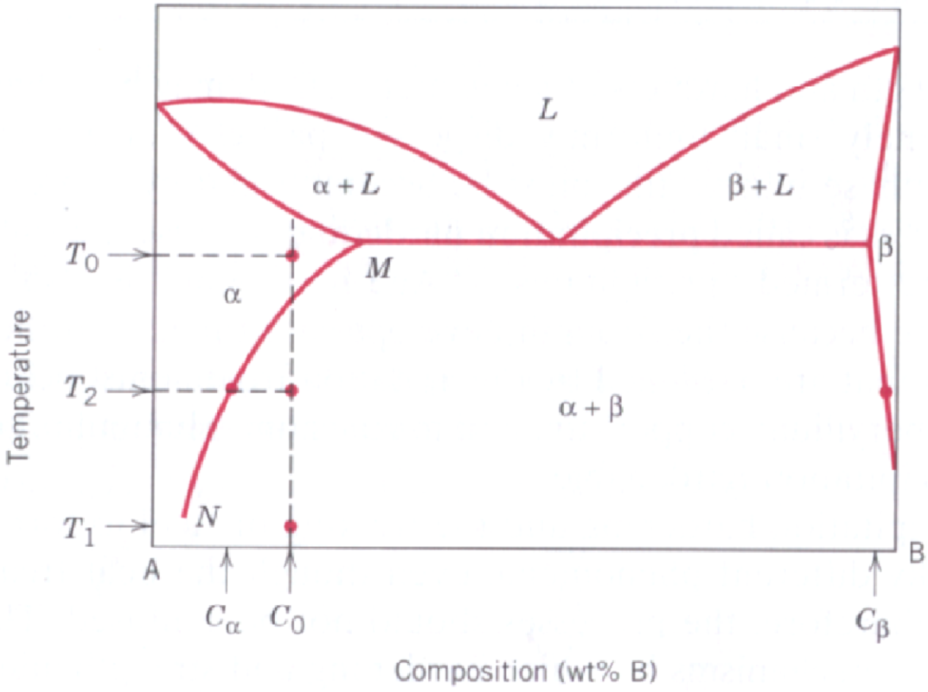


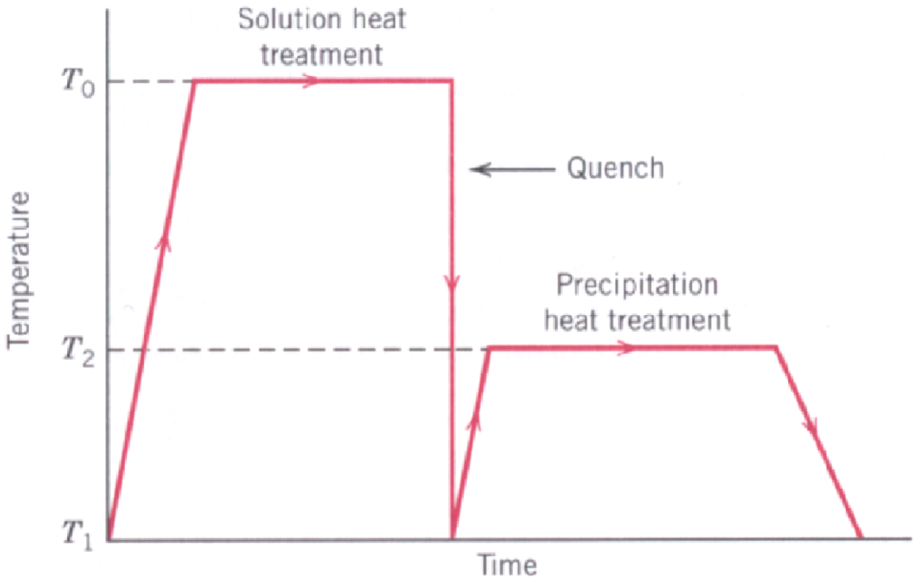
Cold work expressed in terms of area reduction:

$$\%CW = \left(\frac{A_{initial} - A_{final}}{A_{initial}} \right) * 100$$

Precipitation Hardening

- A metal alloy can be hardened and strengthened by precipitating small secondary phase particles from a supersaturated solid solution

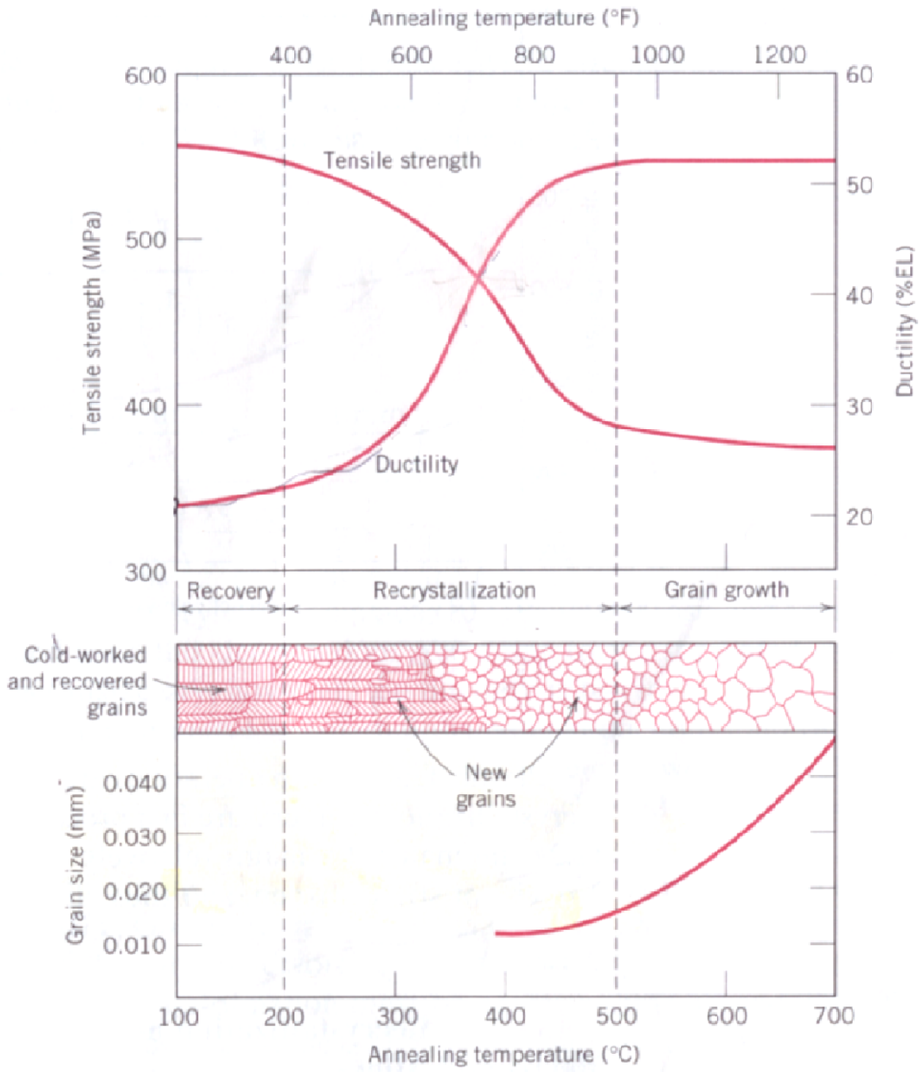




Reference: Callister, W.D. (2000)

Annealing

- Cold Work
- Recovery
- Recrystallization
- Grain Growth



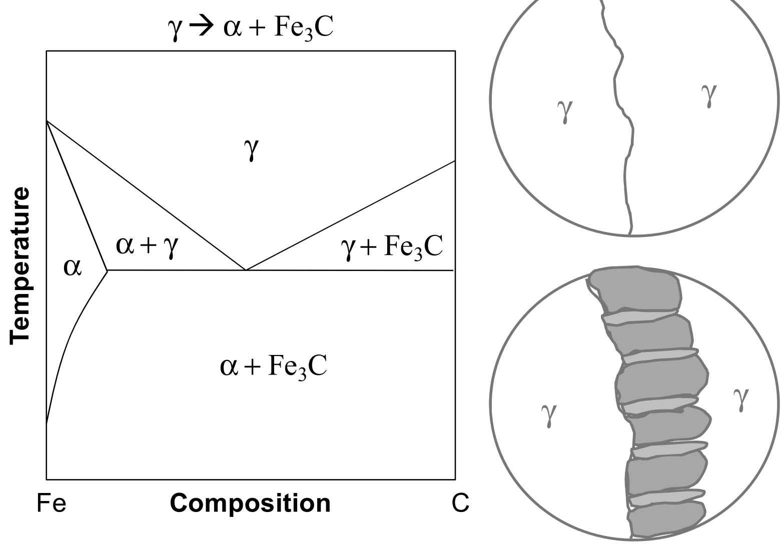
Reference: Callister, W.D. (2000)

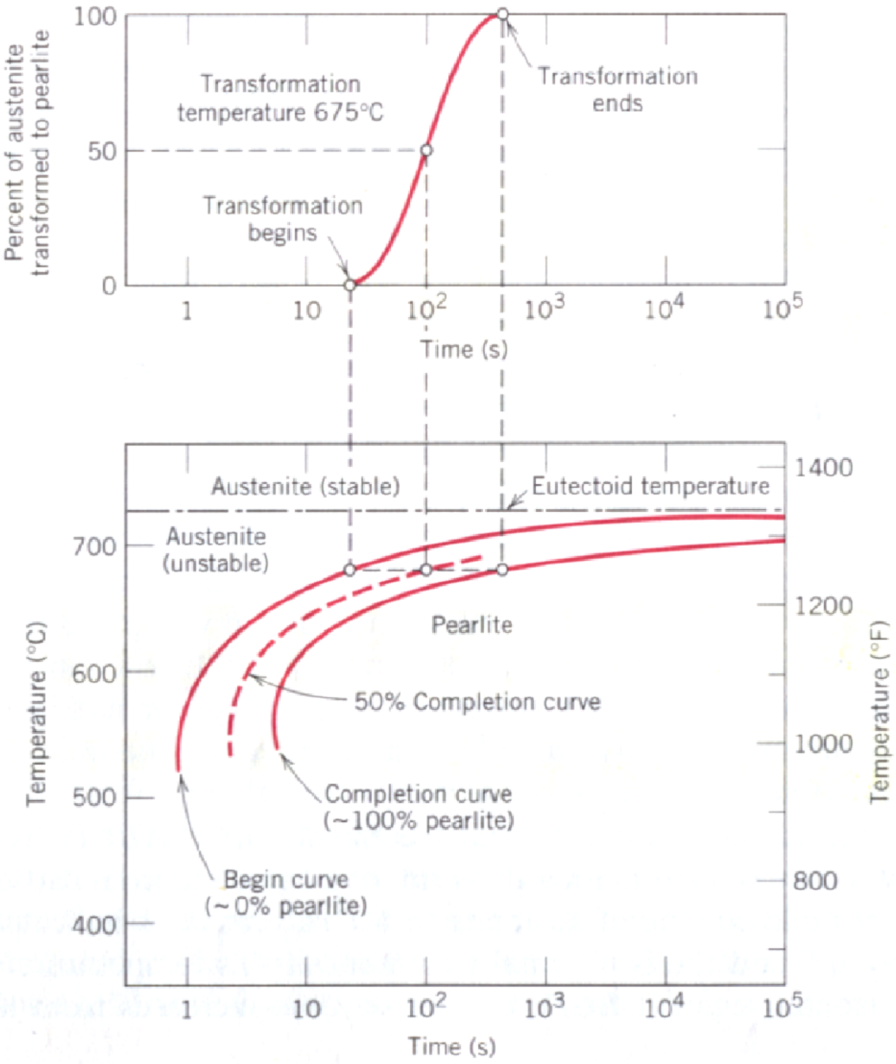
What is a Phase Transformation?

- A change in the number and/or character of phases contained within an alloy
- Three types of transformations
    - Diffusional transformations – No change in the number or composition of the phases present
    - Diffusional transformations – Phase composition and number of phases may change
    - Diffusionless transformations – Metastable phase is produced

Phase Transformations

- Isothermal transformation diagrams (TTT) describe the nucleation and growth behavior at a hold temperature





Reference: Callister, W.D. (2000)

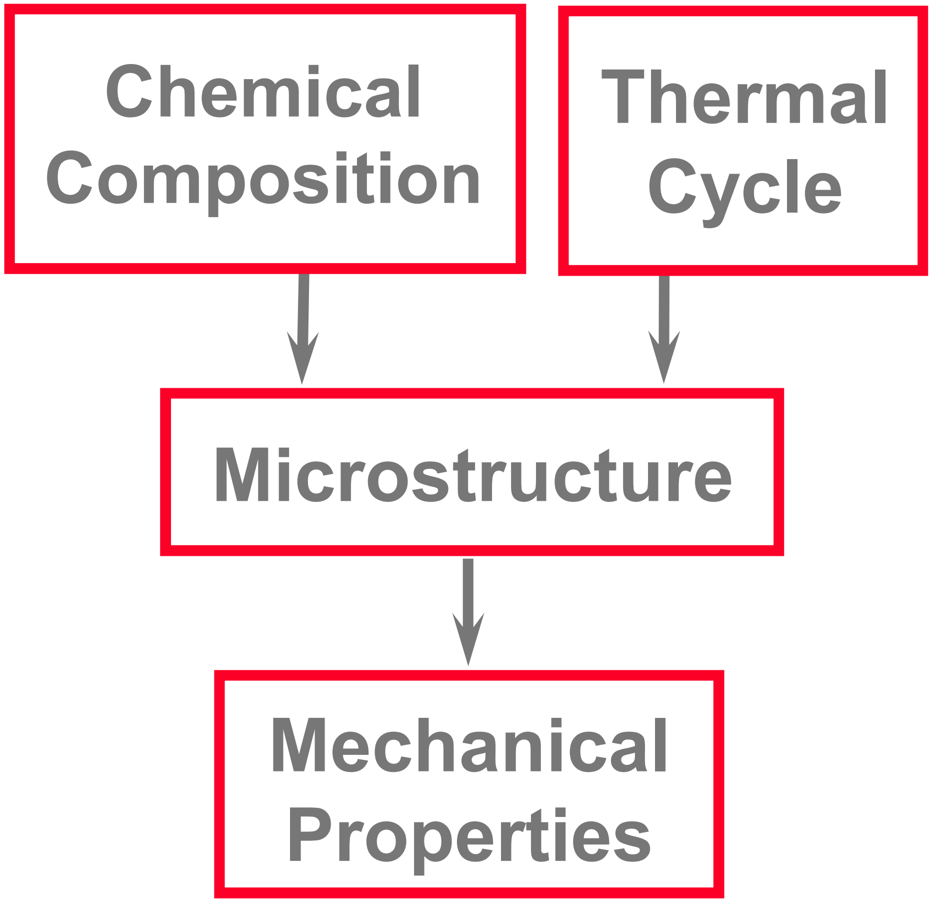
Basics of Welding Metallurgy

Module 3B

Welding Metallurgy

- Welding metallurgy describes a microcosm of metallurgical processes occurring in and around a weld that influence the microstructure, properties, and weldability of the material
- Due to the rapid heating and cooling rates associated with most welding processes, metallurgical reactions often occur under transient, non-equilibrium conditions

Microstructure and Properties



Chemical Composition

Thermal Cycle

Microstructure

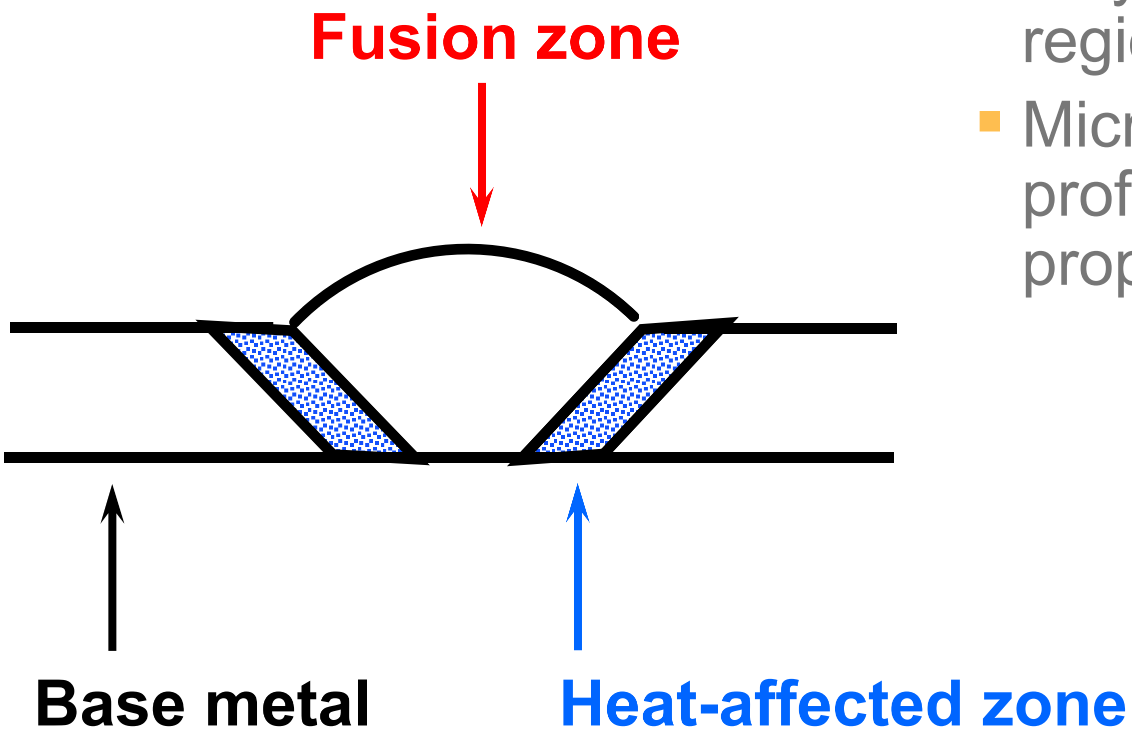
Mechanical Properties

- The cooling rate and chemical composition affect the microstructure of the welded joint
- The mechanical properties of a welded joint depend on the microstructure produced by welding

Metallurgical Processes

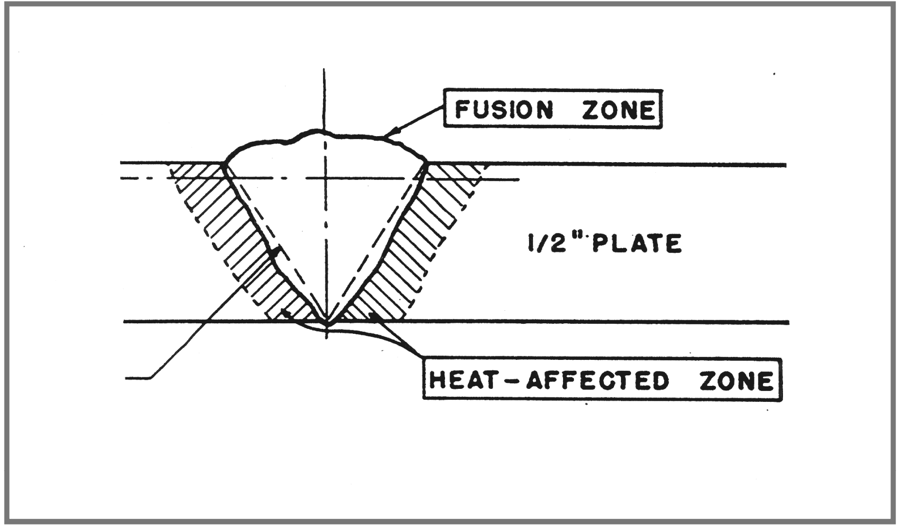
- Melting and solidification
- Nucleation and growth
- Phase transformations
- Segregation and diffusion
- Precipitation
- Recrystallization and grain growth
- Liquation mechanisms
- Embrittlement
- Thermal expansion, contraction, and residual stress

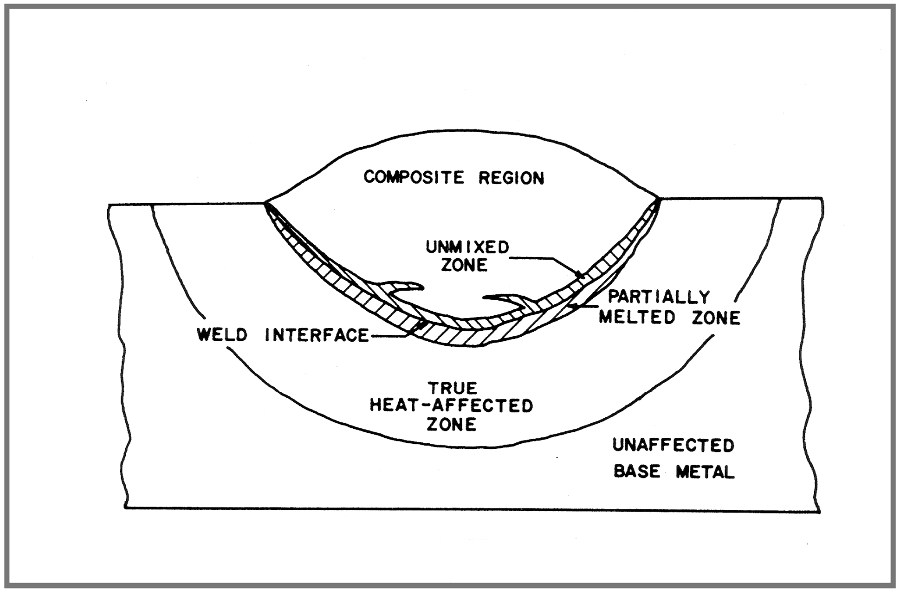
Regions of a Fusion Weld



- The microstructure can vary from region to region in a weld
- Microstructure has a profound effect on weld properties

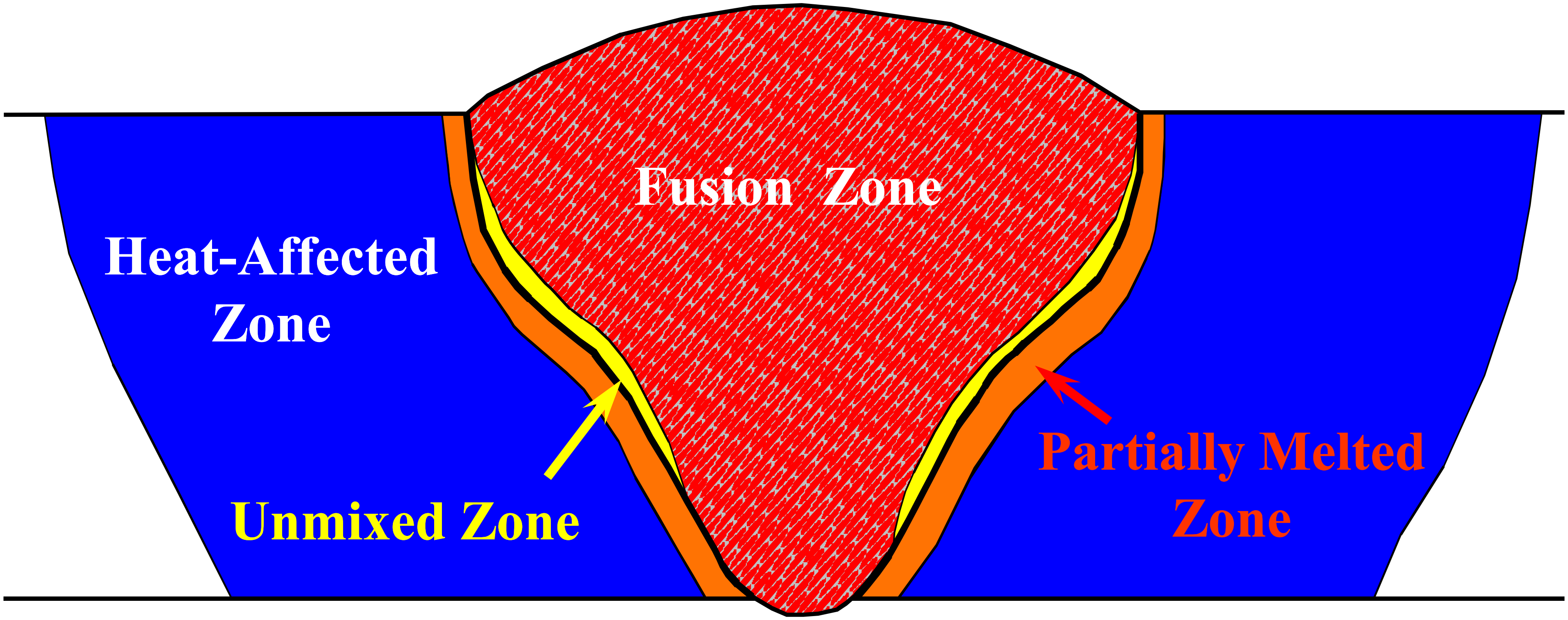
History





- Pre-1976
  - Fusion zone
  - Heat-affected zone
- Post-1976
  - Fusion zone
    - Composite region
    - Unmixed zone
- Heat-affected zone
  - Partially melted zone
  - “True” heat-affected zone

Current



- Fusion zone
  - Composite zone
  - Unmixed zone (UMZ)
- Heat-Affected Zone (HAZ)
  - Partially-melted zone (PMZ)
  - True heat-affected zone (T-HAZ)

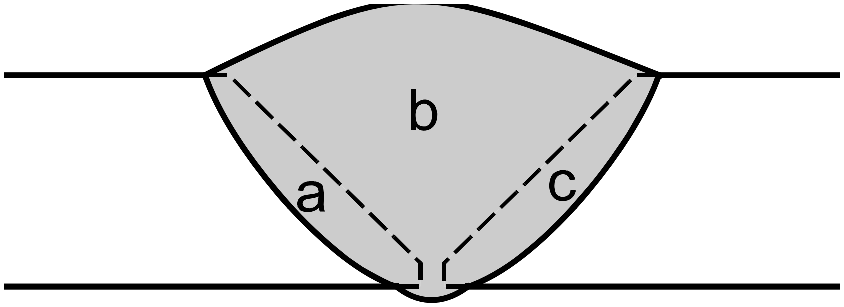
The Fusion Zone

- Region of the weld that is completely melted and resolidified
- Microstructure dependent on composition and solidification conditions
- Local variations in composition
- Distinct from other regions of the weld
- May exhibit three regions
    - Composite zone
    - Transition zone
    - Unmixed zone

Types of Fusion Zones

- Autogenous
  - No filler metal addition
  - GTAW on thin sheet, EBW of square butt joint
- Homogeneous
  - Addition of filler metal of matching composition
  - 4130 filler used to join 4130 Cr-Mo steel
- Heterogeneous
  - Addition of filler metal with dissimilar composition to the base material
  - 4043 filler used to join 6061 aluminum
  - Ni-based alloys for joining stainless steels

Dilution



$$\text{Dilution (\%)} = \frac{a + c}{a + b + c} \times 100$$

- Amount of melted base metal mixing with filler
- Expressed as percent base metal dilution of the filler metal
  - 100% is an autogenous weld
  - 10-40% common in arc welds
- Significant effect on microstructure and properties
- Controlled by joint design, process, and parameters

Dilution of 308L SS Filler Metal by 304 SS Base Metal

High Dilution

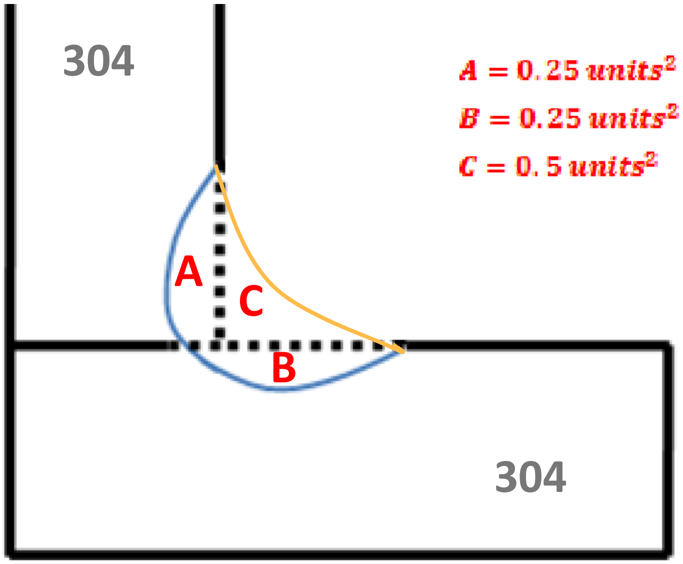


Figure 1

$$\text{High Dilution }\% = \frac{\text{base metal area}}{\text{weld metal (nugget area)}} = \frac{A+B}{A+B+C}$$

$$= \frac{0.25\ units^2 + 0.25\ units^2}{0.25\ units^2 + 0.25\ units^2 + 0.5\ units^2}$$

$$= \frac{0.5\ units^2}{1\ unit^2} = 50\%$$

Low Dilution

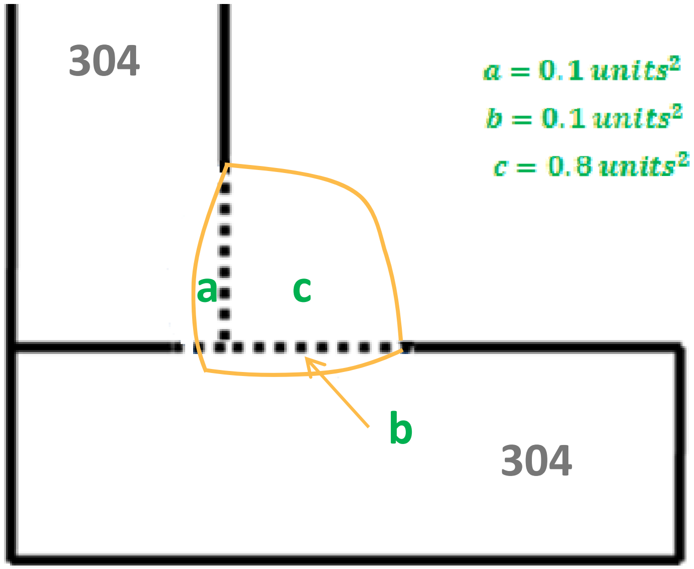


Figure 2

$$\text{Low Dilution }\% = \frac{\text{base metal area}}{\text{weld metal (nugget area)}} = \frac{a+b}{a+b+c}$$

$$= \frac{0.1\ units^2 + 0.1\ units^2}{0.1\ units^2 + 0.1\ units^2 + 0.8\ units^2}$$

$$= \frac{0.2\ units^2}{1\ unit^2} = 20\%$$

Dilution of 4043 Filler Metal by 6061 Aluminum Base Metal

High Dilution

V-Groove **without** Root Opening

$A = 0.25\ units^2$

$B = 0.2\ units^2$

$C = 0.55\ units^2$

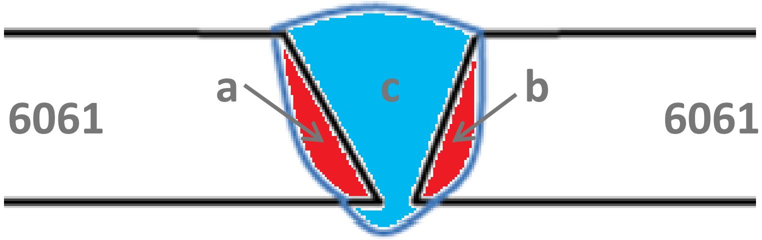
$$High\ Dilution\ \% = \frac{base\ metal\ area}{weld\ metal\ (nugget\ area)} = \frac{A+B}{A+B+C}$$

$$= \frac{0.25\ units^2 + 0.2\ units^2}{0.25\ units^2 + 0.2\ units^2 + 0.55\ units^2}$$

$$= \frac{0.45\ units^2}{1\ unit^2} = 45\%$$

Low Dilution

V-Groove **with** Root Opening



$a = 0.08\ units^2$

$b = 0.07\ units^2$

$c = 0.85\ units^2$

$$Low\ Dilution\ \% = \frac{base\ metal\ area}{weld\ metal\ (nugget\ area)} = \frac{a+b}{a+b+c}$$

$$= \frac{0.08\ units^2 + 0.07\ units^2}{0.08\ units^2 + 0.07\ units^2 + 0.85\ units^2}$$

$$= \frac{0.15\ units^2}{1\ unit^2} = 10\%$$

Dilution of 4043 Filler Metal by 6061 Aluminum Base Metal

Material	Cu	Fe	Mg	Mn	Si
6061	0.25	0.50	1.10	0.12	0.55
4043	0.30	0.80	0.05	0.05	5.20

High Dilution

45%	Cu	Fe	Mg	Mn	Si
Weld Metal	0.278	0.665	0.523	0.082	3.108

$$WM_{45\%}^{Cu} = (45\% * 0.25) + (55\% * 0.30) = 0.278$$

$$WM_{45\%}^{Fe} = (45\% * 0.50) + (55\% * 0.80) = 0.665$$

$$WM_{45\%}^{Mg} = (45\% * 1.10) + (55\% * 0.05) = 0.523$$

$$WM_{45\%}^{Mn} = (45\% * 0.12) + (55\% * 0.05) = 0.082$$

$$WM_{45\%}^{Si} = (45\% * 0.55) + (55\% * 5.20) = 3.108$$

Low Dilution

10%	Cu	Fe	Mg	Mn	Si
Weld Metal	0.295	0.770	0.155	0.057	4.735

$$WM_{10\%}^{Cu} = (10\% * 0.25) + (90\% * 0.30) = 0.295$$

$$WM_{10\%}^{Fe} = (10\% * 0.50) + (90\% * 0.80) = 0.77$$

$$WM_{10\%}^{Mg} = (10\% * 1.10) + (90\% * 0.05) = 0.155$$

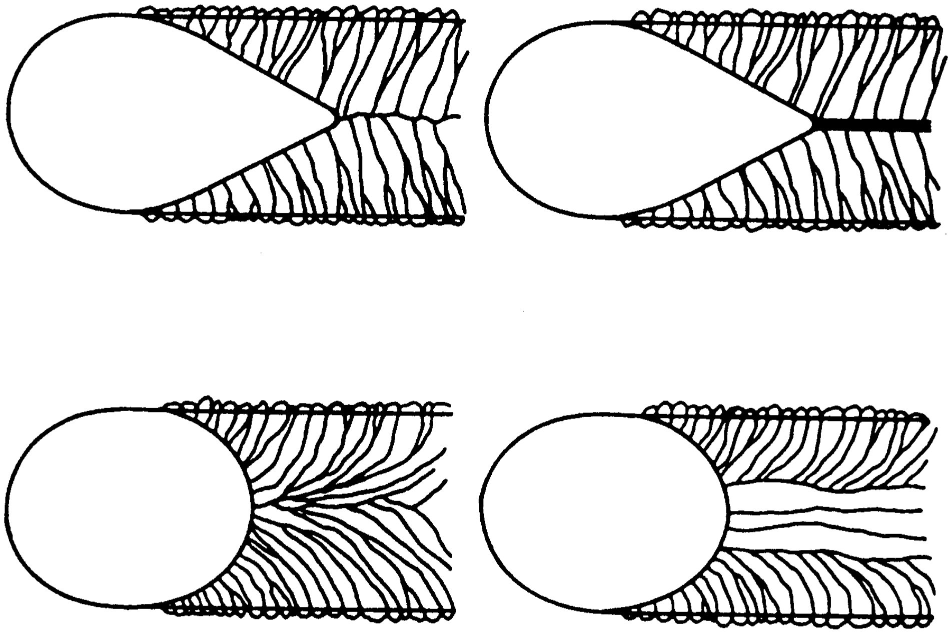
$$WM_{10\%}^{Mn} = (10\% * 0.12) + (90\% * 0.05) = 0.057$$

$$WM_{10\%}^{Si} = (10\% * 0.55) + (90\% * 5.20) = 4.735$$

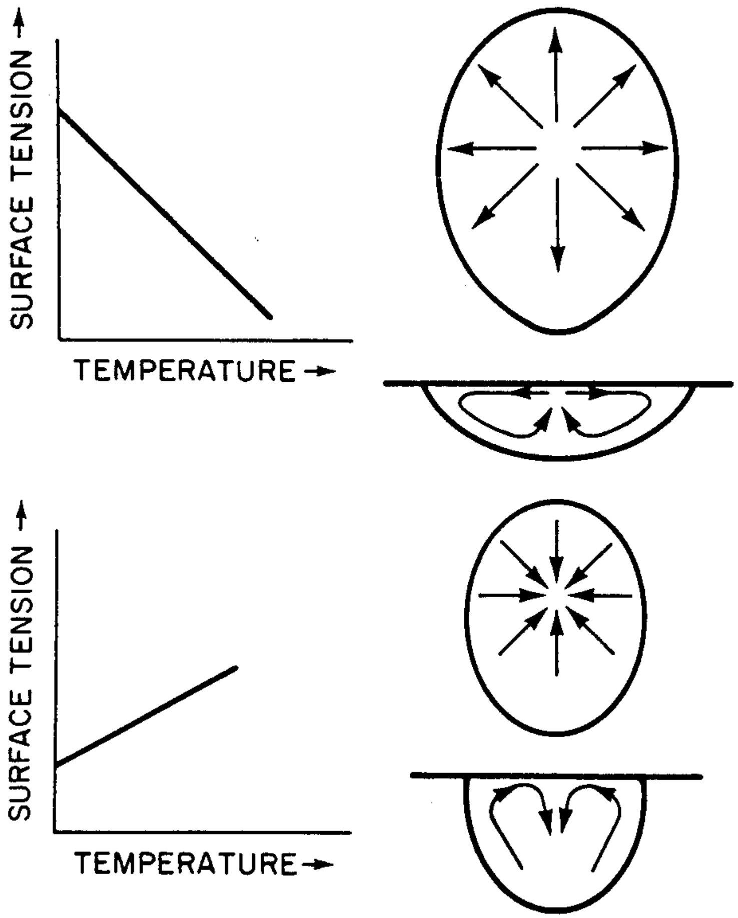
Silicon levels above 4 wt% help prevent weld solidification cracking

Weld Pool Shape

- Material properties
  - Melting point
  - Thermal conductivity
  - Surface tension
    - Marangoni effect
- Process parameters
  - Heat input
  - Travel speed
- Heat flow conditions
  - 2-D (full penetration)
  - 3-D (partial penetration)



Surface Tension Induced Fluid Flow



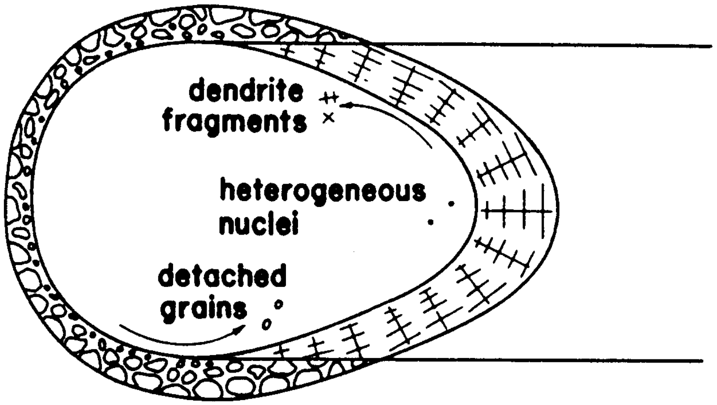
- Surface tension of liquid a function of composition and temperature
  - Marongoni effect
- Influence of gradient on weld pool fluid flow
  - Negative gradient promotes outward flow and shallow penetration
  - Positive gradient promotes inward (downward) flow and good penetration
- Strong influence of sulfur and oxygen

Figure modified from Heiple and Roper

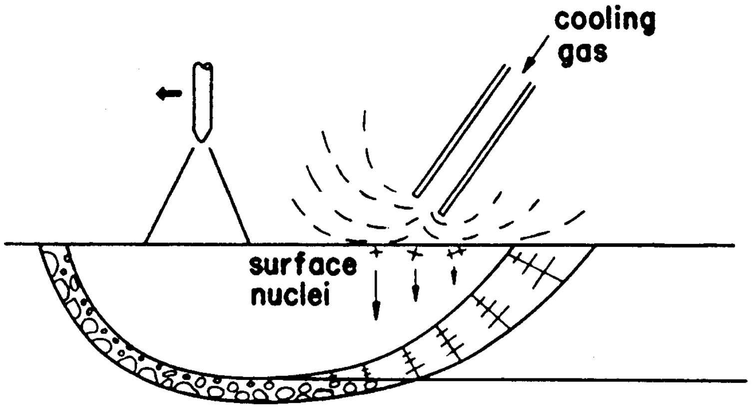
Nucleation of Solid during Solidification

- Homogeneous
  - Critical radius size, where $r^* = \frac{2\gamma slTm}{\Delta HM\ \Delta T}$
  - Liquid undercooling
- Heterogeneous
  - Nucleation from existing substrate or particle
  - Little or no undercooling required

Types of Heterogeneous Nucleation



MECHANISM 1 : Dendrite Fragmentation
MECHANISM 2: Grain Detachment
MECHANISM 3: Heterogeneous Nucleation

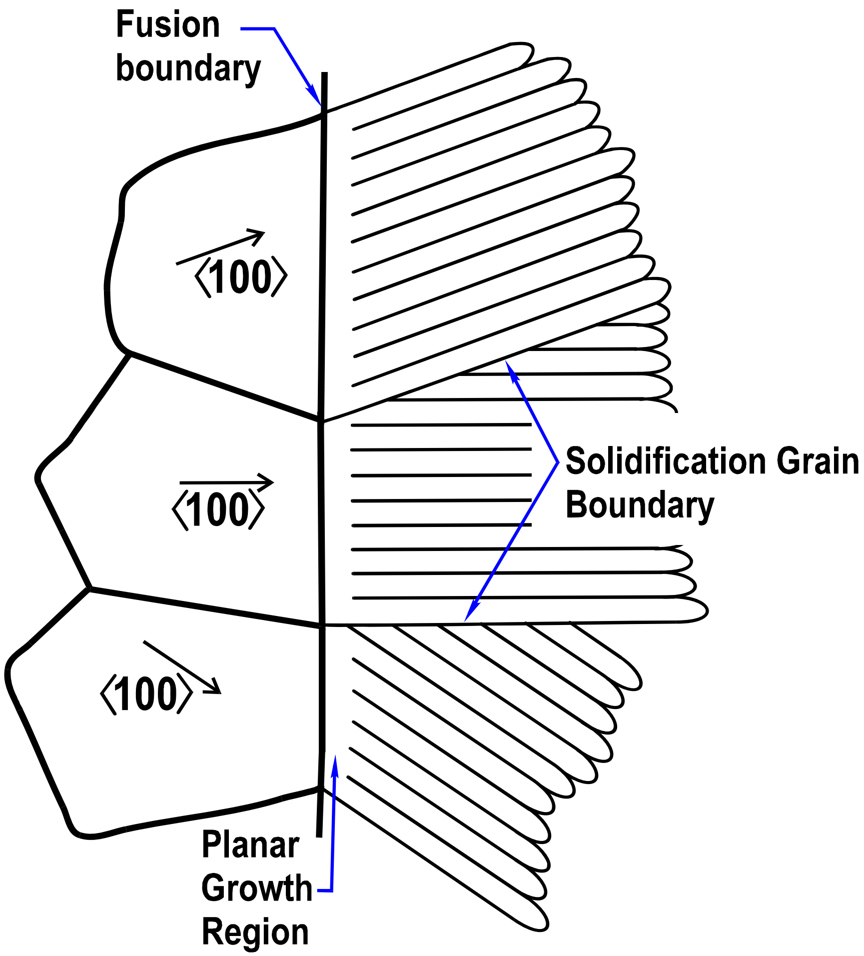


MECHANISM 4: Surface Nucleation

- Dendrite fragmentation
- Grain detachment
- Nucleant particle formation
- Surface nucleation
- Epitaxial nucleation

Courtesy Kou and Le

Epitaxial Nucleation at the Fusion Boundary

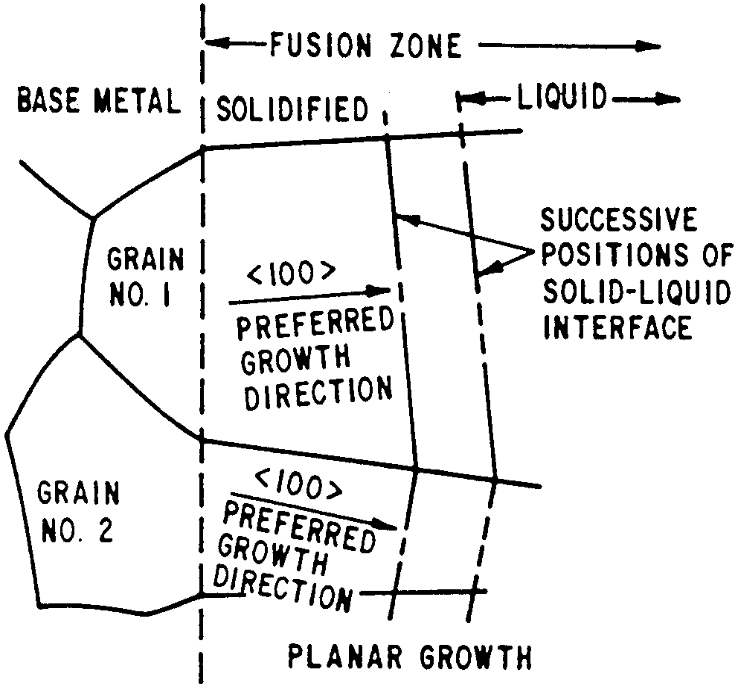


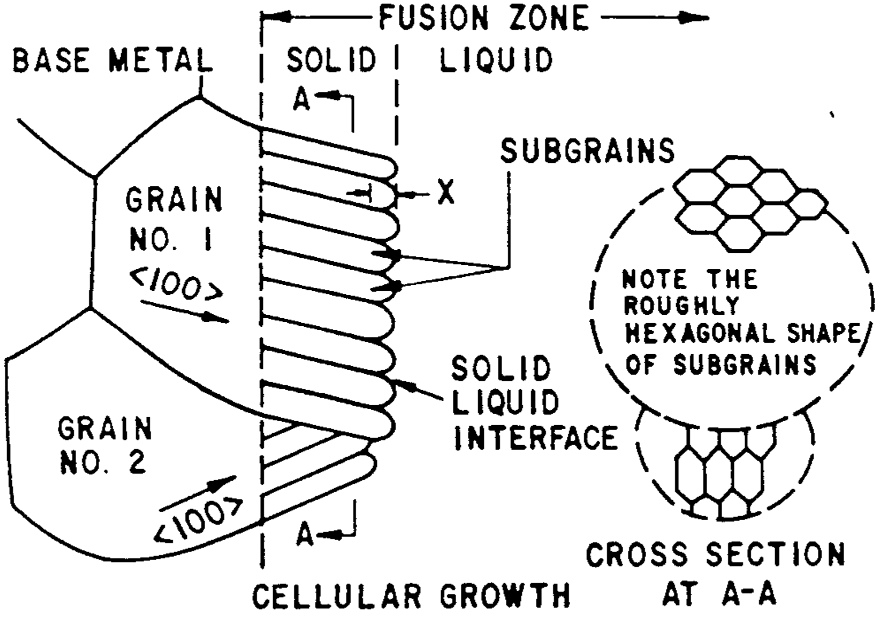
- Nucleation from an existing solid substrate
- Crystallographic orientation of base metal “seed crystal” is maintained
- Growth parallel to cube edge in cubic materials
  - ⟨100⟩ in FCC and BCC
  - ⟨1010⟩ in HCP
  - Called “easy growth” directions

Solidification Modes

- Multiple solidification modes (morphologies) are possible
  - Planar
  - Cellular
  - Cellular dendritic
  - Columnar dendritic
  - Equiaxed dendritic
- Controlled by
  - Temperature gradient in the liquid, G_L
  - Solidification growth rate, R
  - Composition

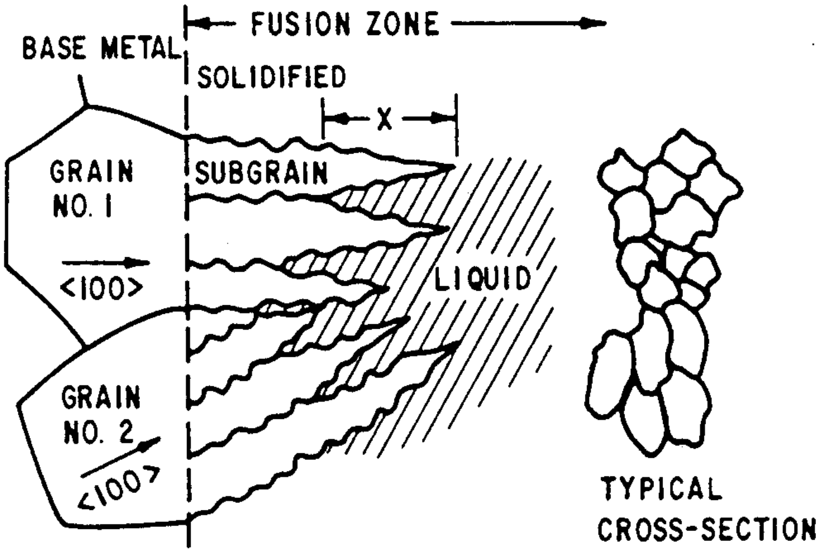
Solidification Growth Modes



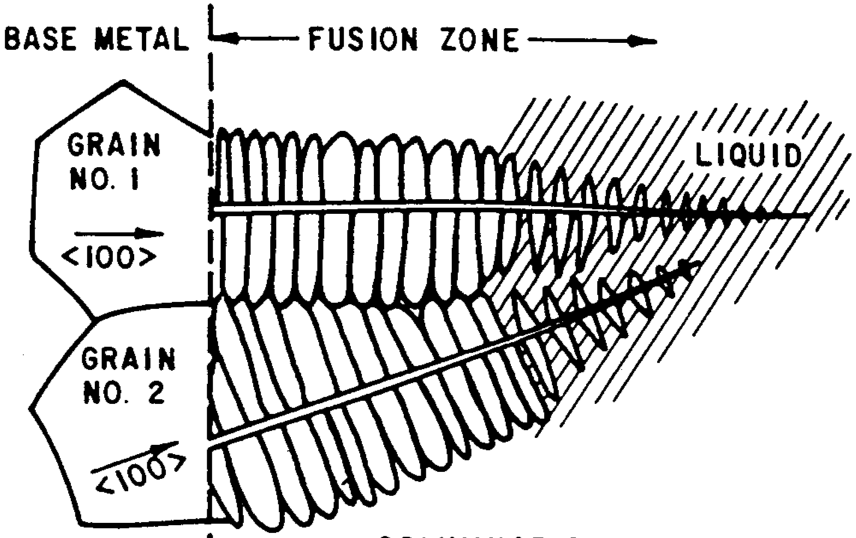


High G_L and Low R

Solidification Growth Modes

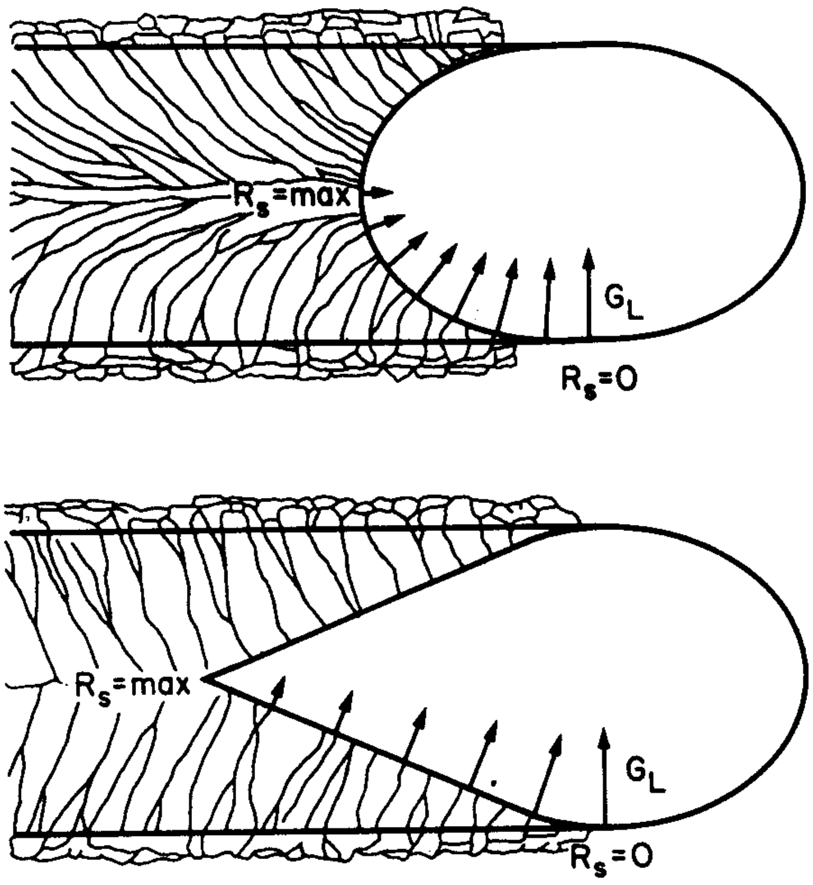


CELLULAR DENDRITIC GROWTH



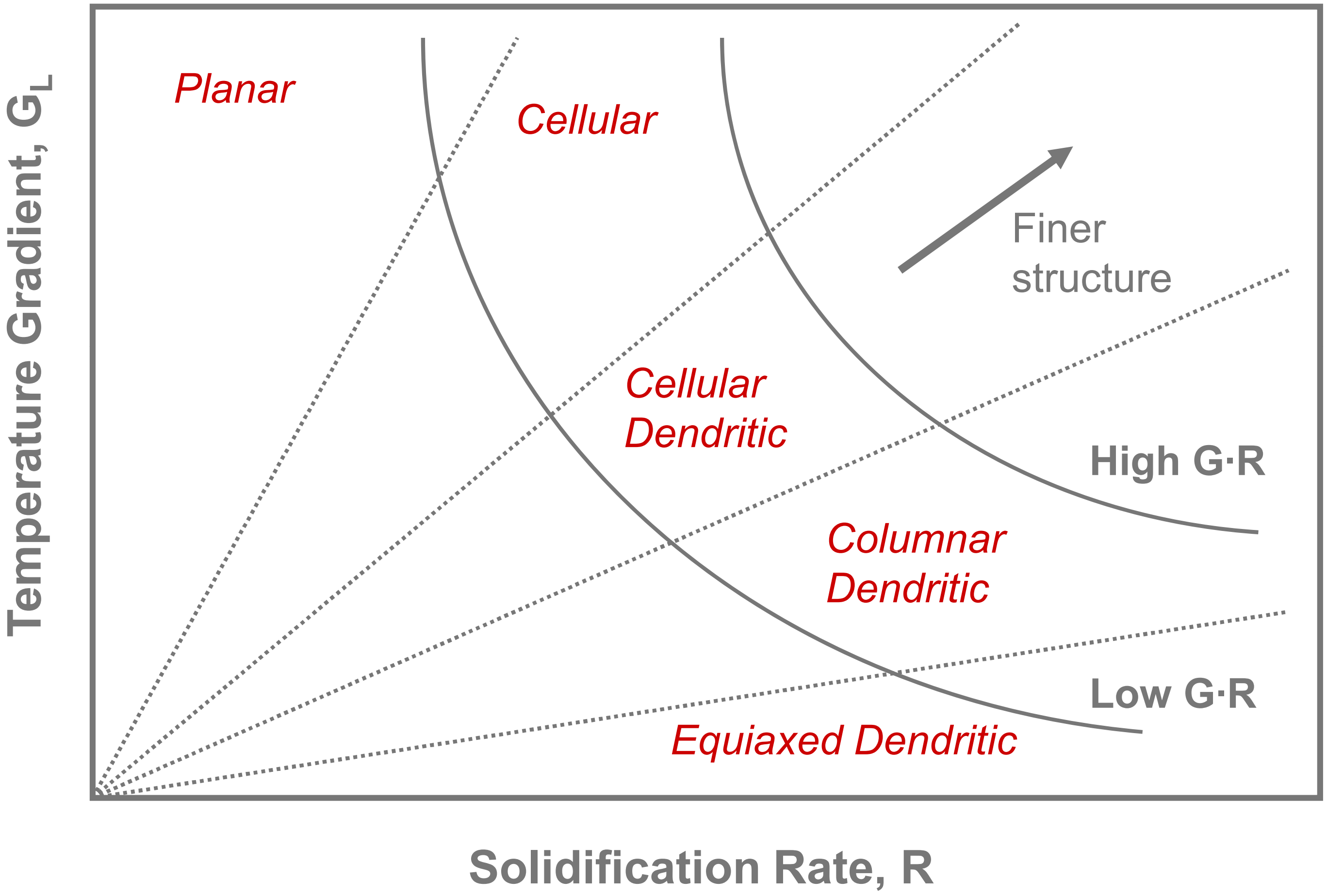
COLUMNAR DENDRITIC GROWTH

Effect of Travel Speed

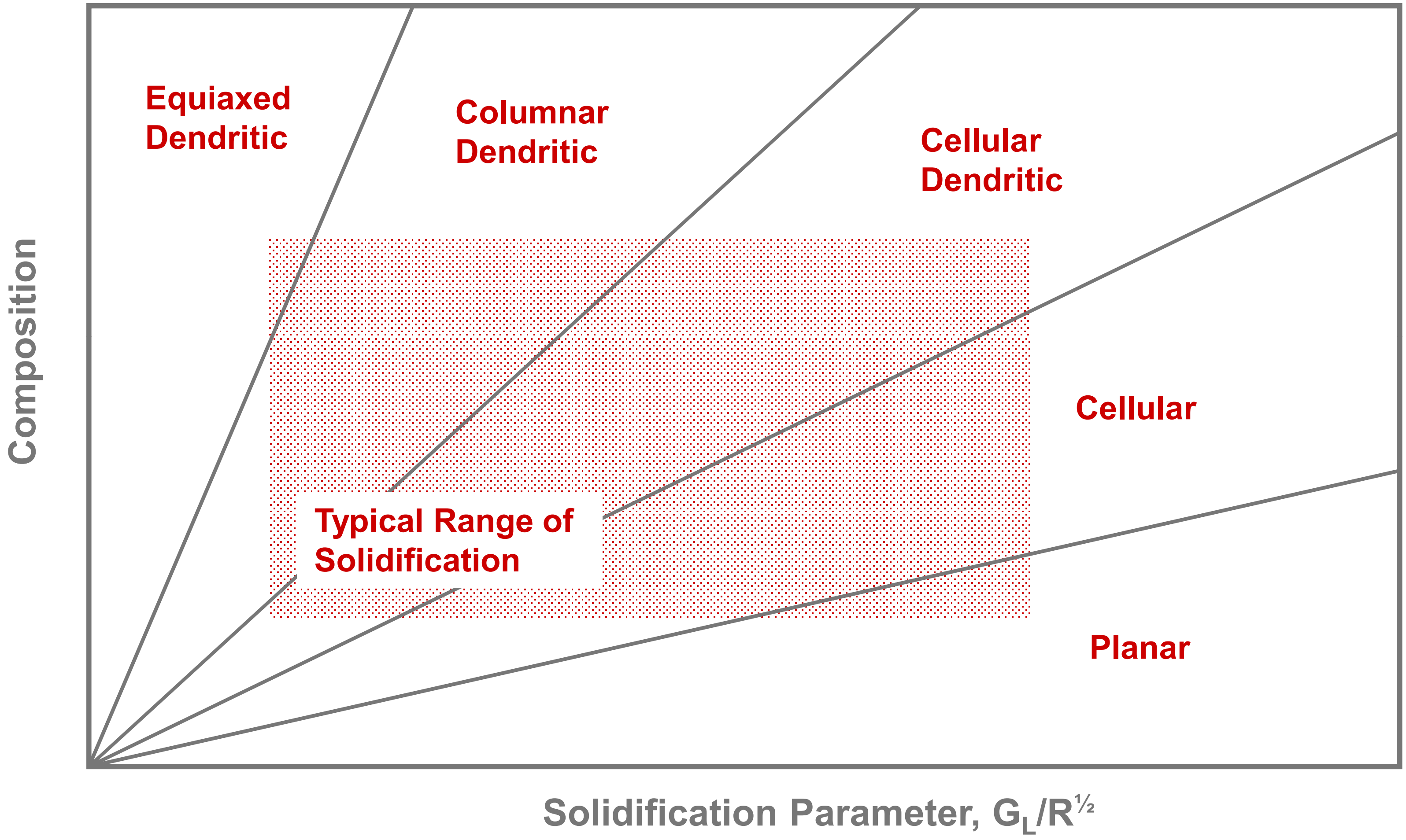


- Travel speed has significant effect on weld pool shape
- Low travel speeds
  - Elliptical pool shape
  - Curved columnar grains
  - Gradual change in GL and R
- High travel speeds
  - Teardrop pool shape
  - Distinct centerline
  - R is constant along most of S-L interface

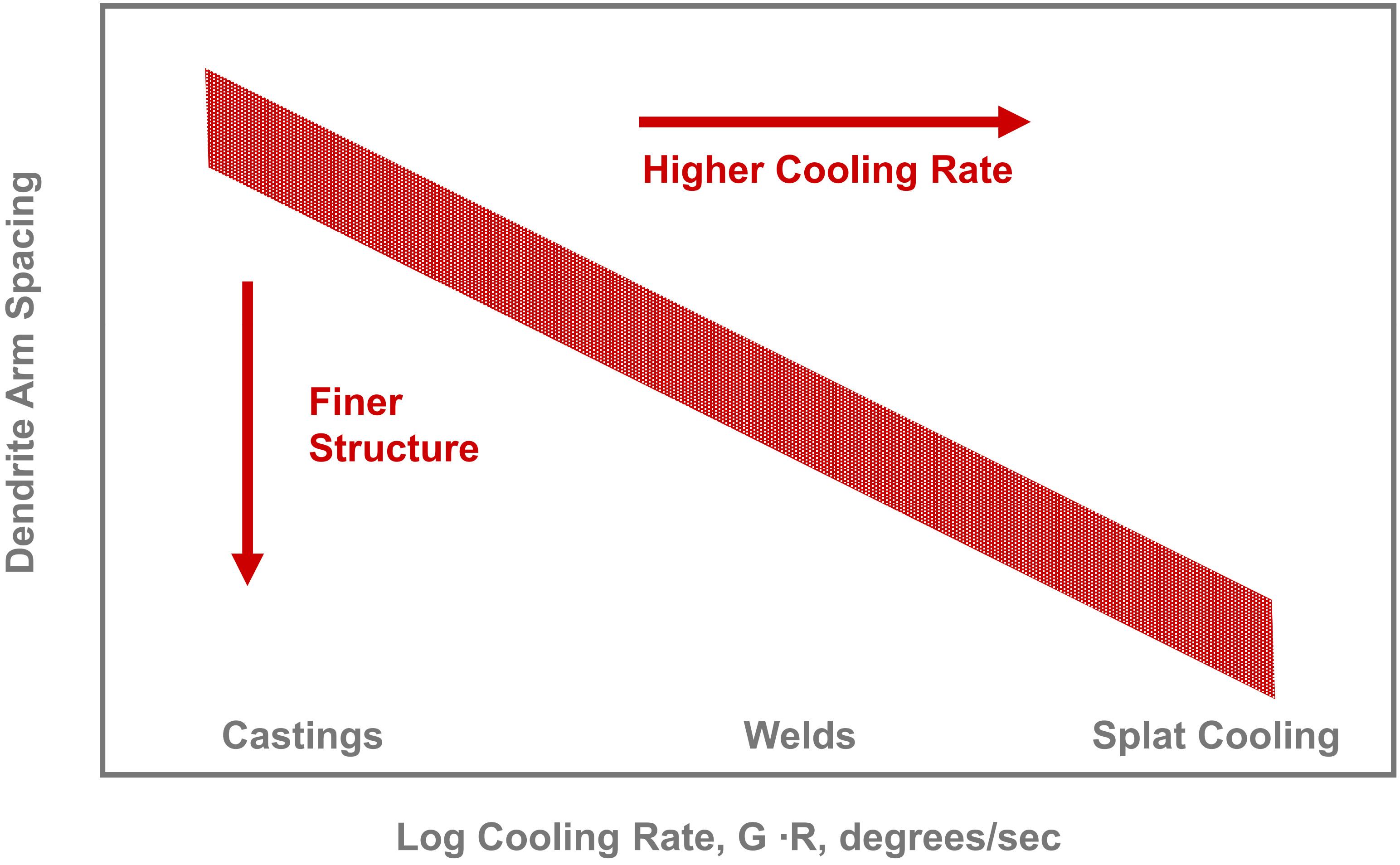
Effect of G_L and R



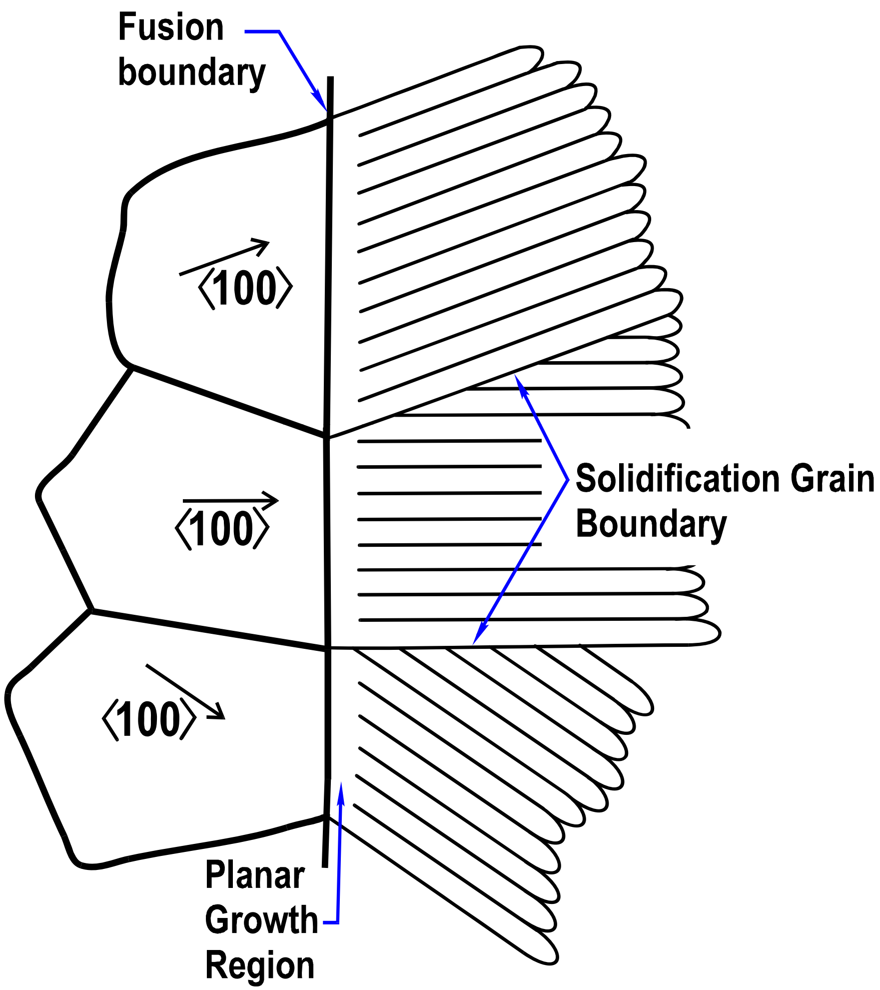
Effect of G_L, R, and Composition



Effect of Cooling Rate

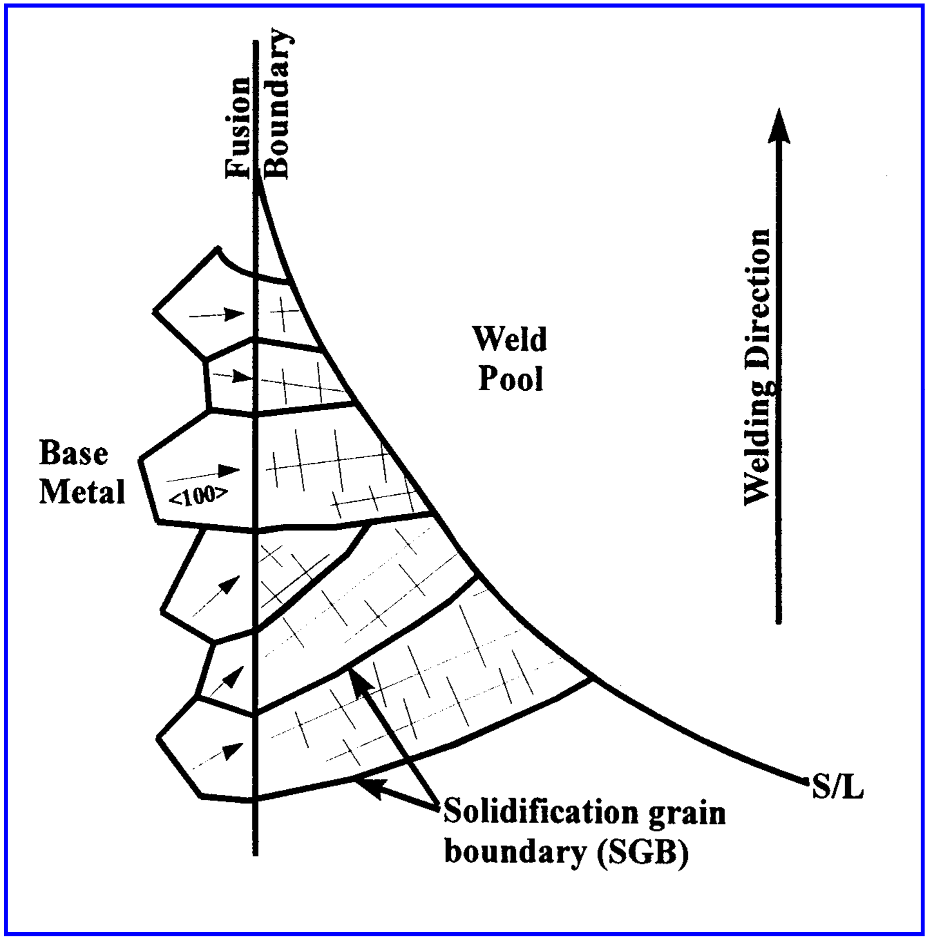


Weld Metal Epitaxial Nucleation



- Nucleation from and existing solid substrate at the fusion boundary
- Crystallographic orientation of HAZ grain is maintained
- “Easy growth” directions parallel to cube edge in cubic materials
  - ⟨100⟩ in FCC and BCC
  - ⟨1010⟩ in HCP

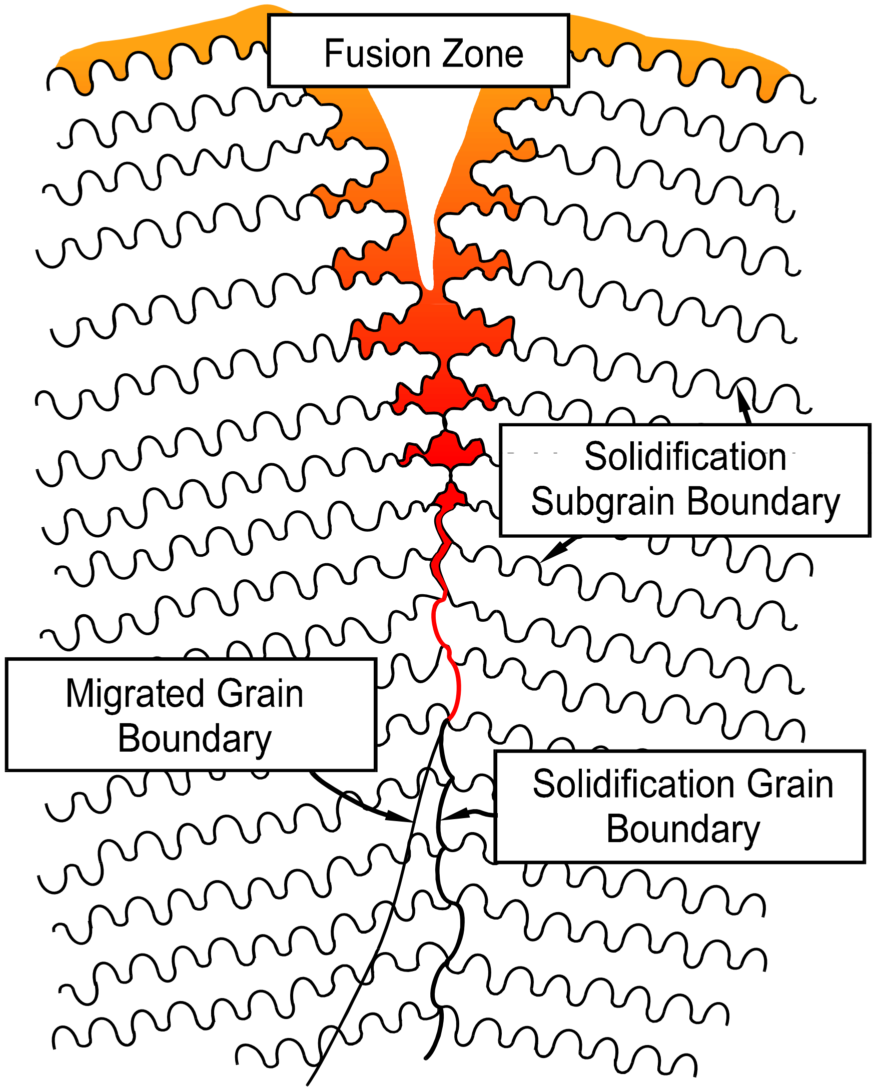
Competitive Growth



- Random orientation of base metal grains in polycrystalline materials
- Growth most favorable when easy growth direction is parallel to heat flow direction
- Grains “compete” depending on orientation
- Intersection of grains forms SGBs

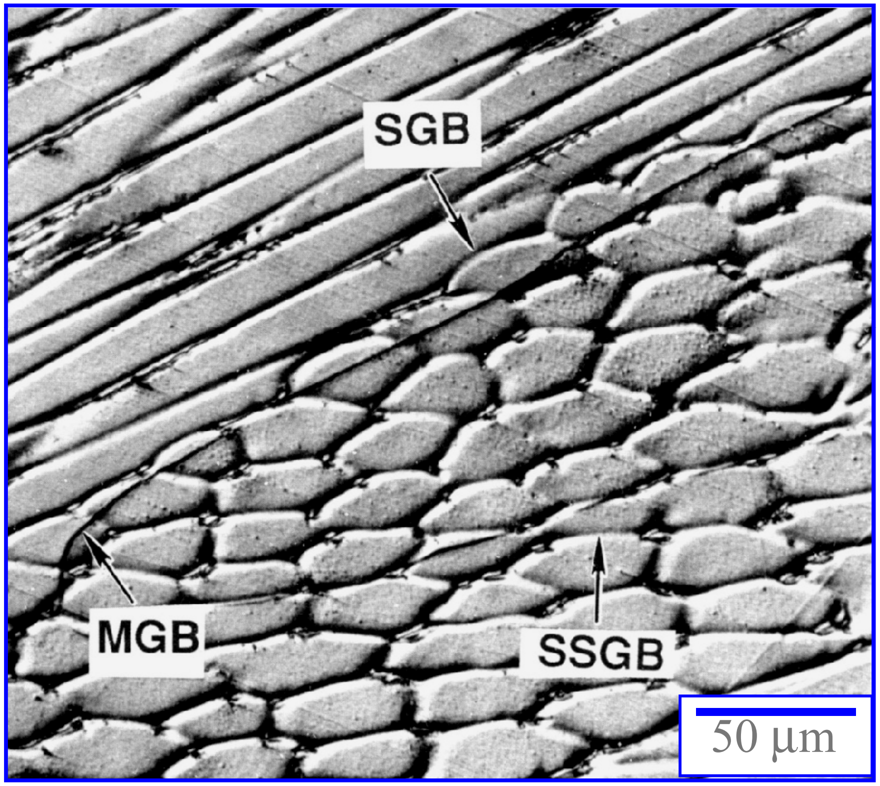
From Nelson and Lippold

Fusion Zone Boundaries



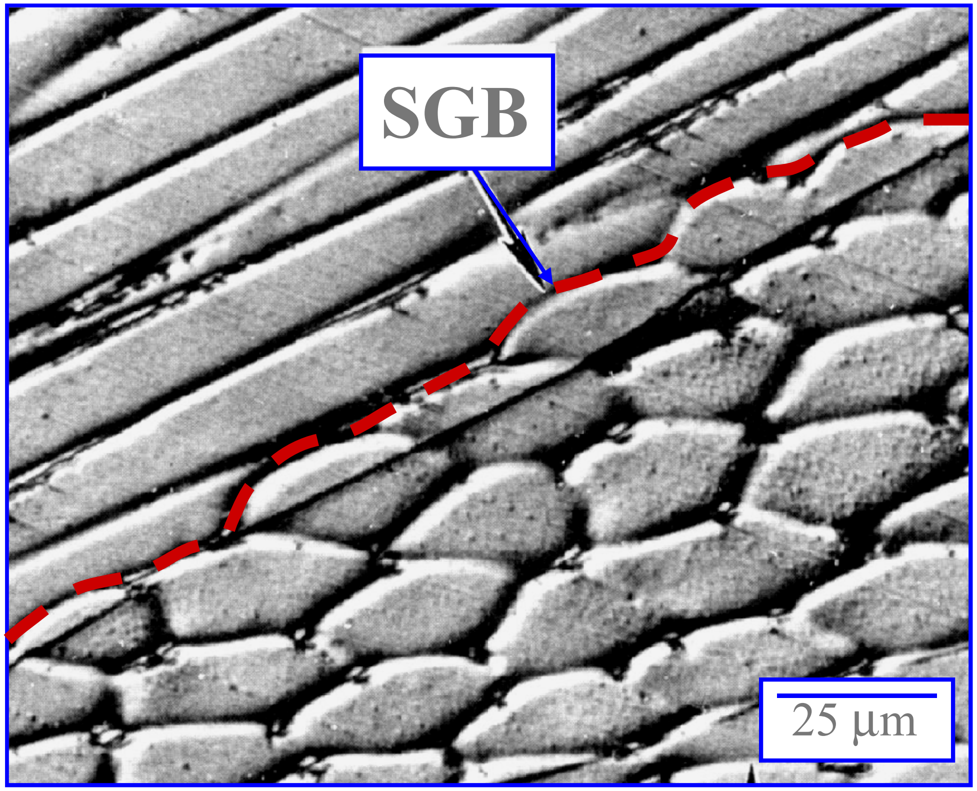
- Differentiated by
  - Composition
  - Structure
- Solidification subgrain boundaries (SSGBs)
  - Composition (Case 2)
  - Low angle misorientation
- Solidification grain boundaries (SGBs)
  - Composition (Case 3)
  - High or low angle misorientation
- Migrated grain boundaries (MGBs)
  - Local variation in composition
  - High angle misorientation

Solidification Subgrain Boundary



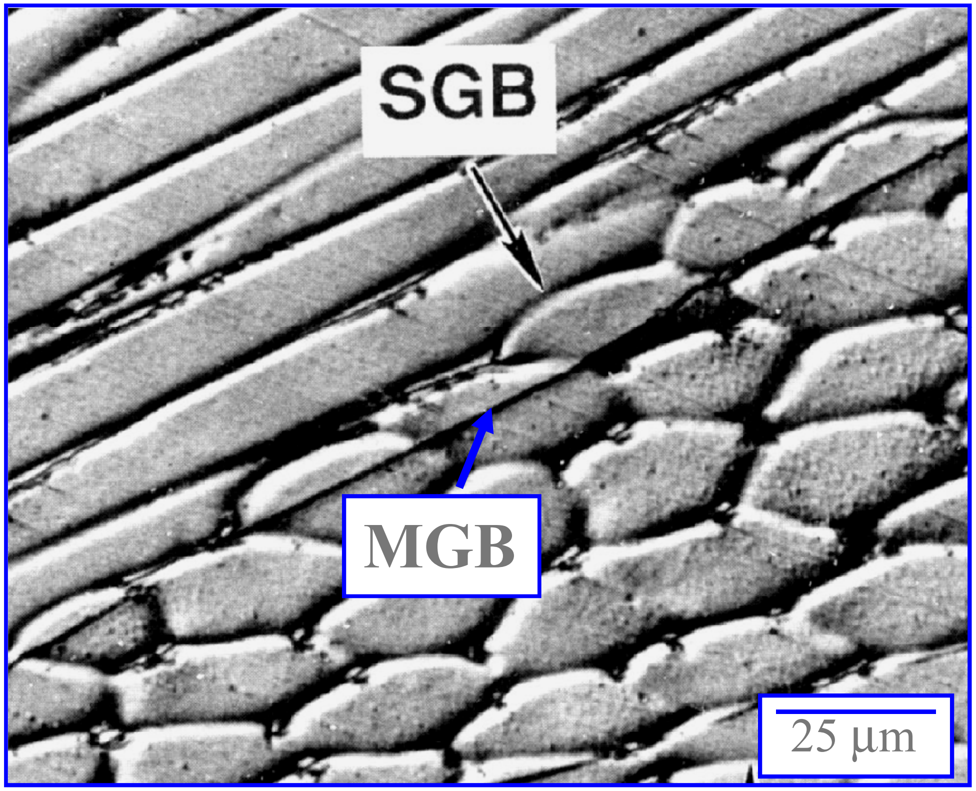
- Boundaries between cells and dendrites (solidification subgrains)
- Composition dictated by Case 2 solute redistribution
- Low misorientation between adjacent subgrains - low angle boundary

Solidification Grain Boundary



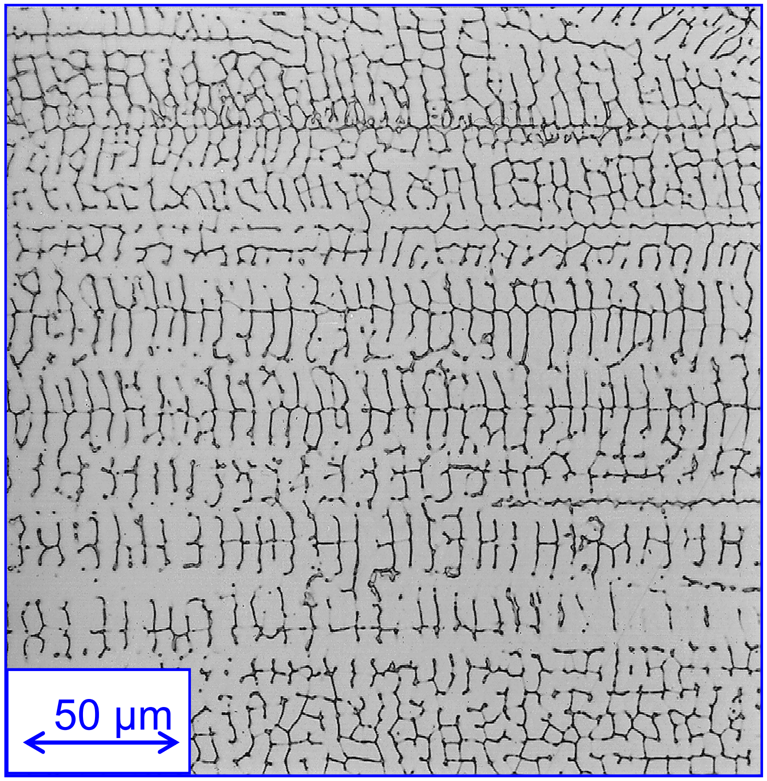
- Boundary between packets of subgrains
- Results from competitive growth
- Composition dictated by Case 3 solute redistribution
- Large misorientation across boundary at end of solidification - high angle boundary
- Most likely site for solidification cracking

Migrated Grain Boundary

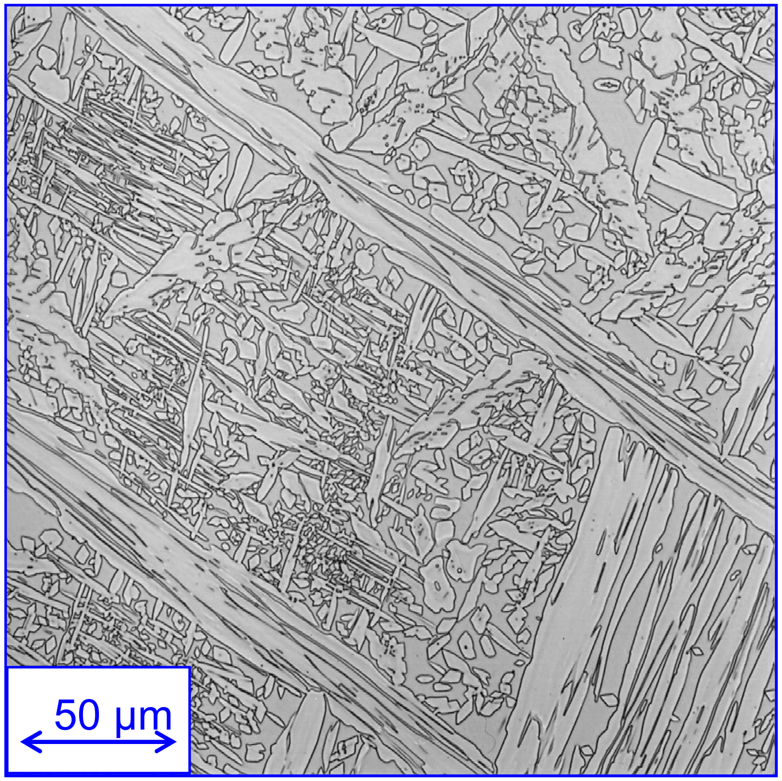


- Crystallographic component of SGB
- Migrates away from SGB in the solid state following solidification or during reheating
- Large misorientation across boundary - high angle boundary
- Composition varies locally
- Possible boundary “sweeping” and segregation
- Liquation and ductility dip cracking

Fusion Zone Microstructure - Stainless Steels

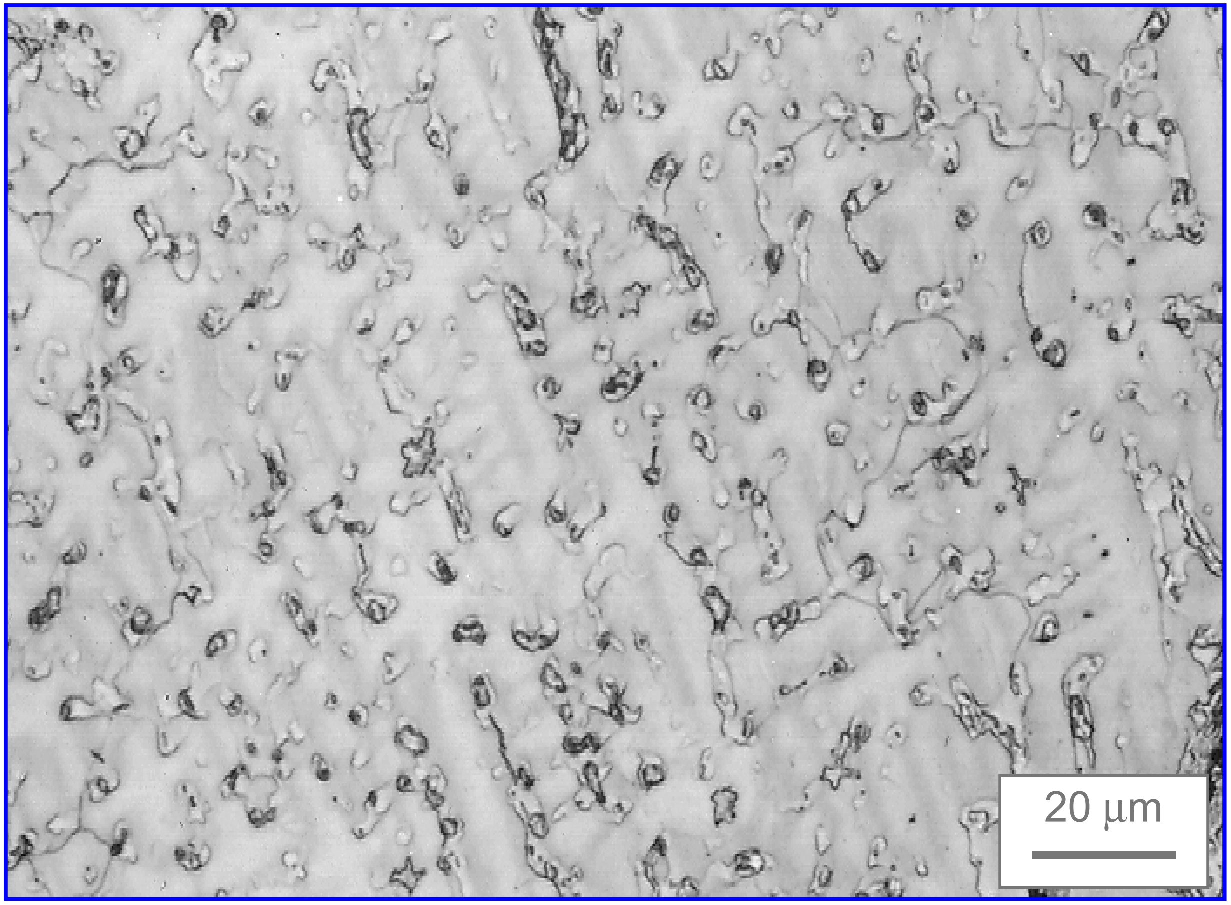


Austenitic Stainless Steel

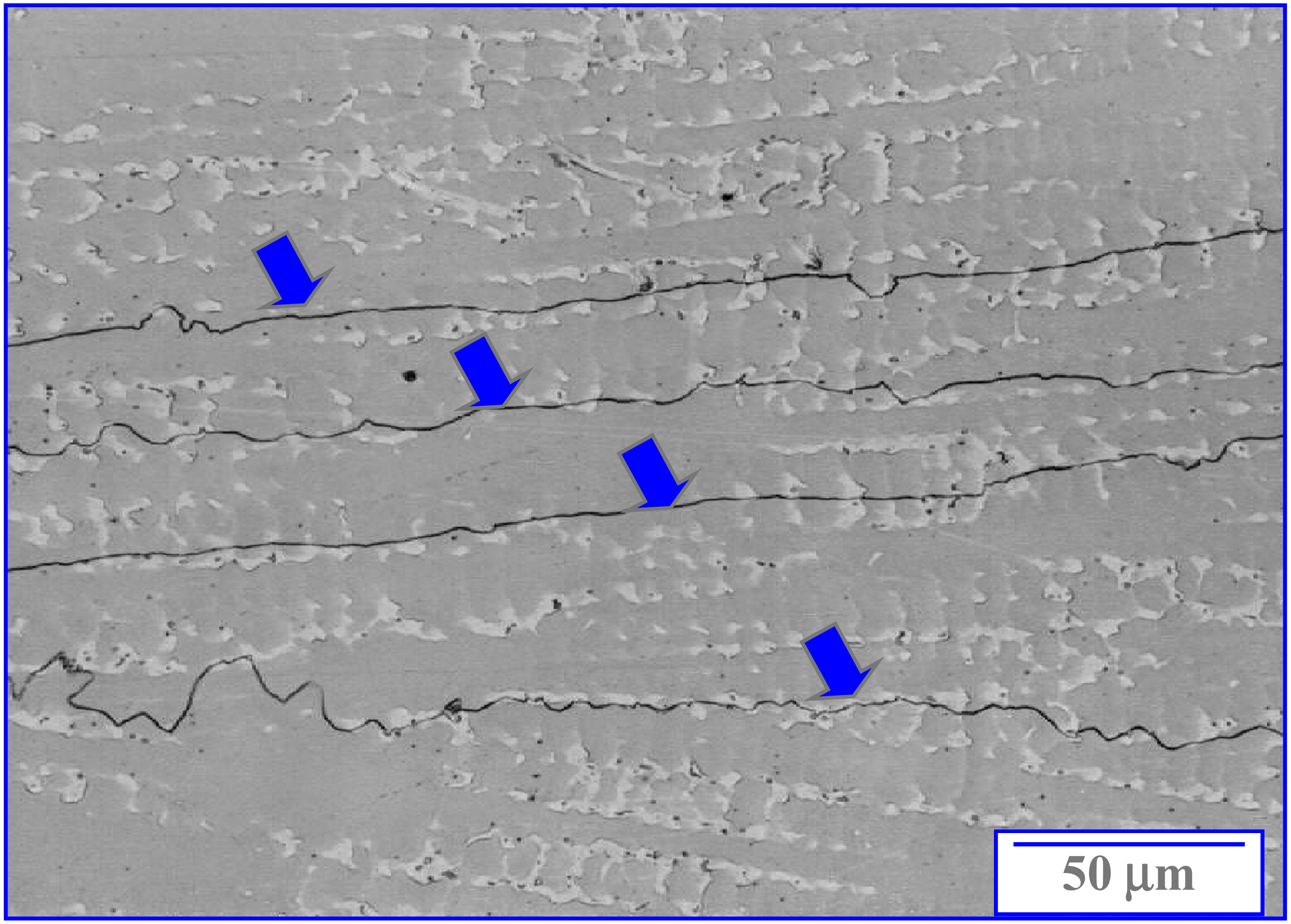


Duplex Stainless Steel

Microstructure - Ni-Base Alloy

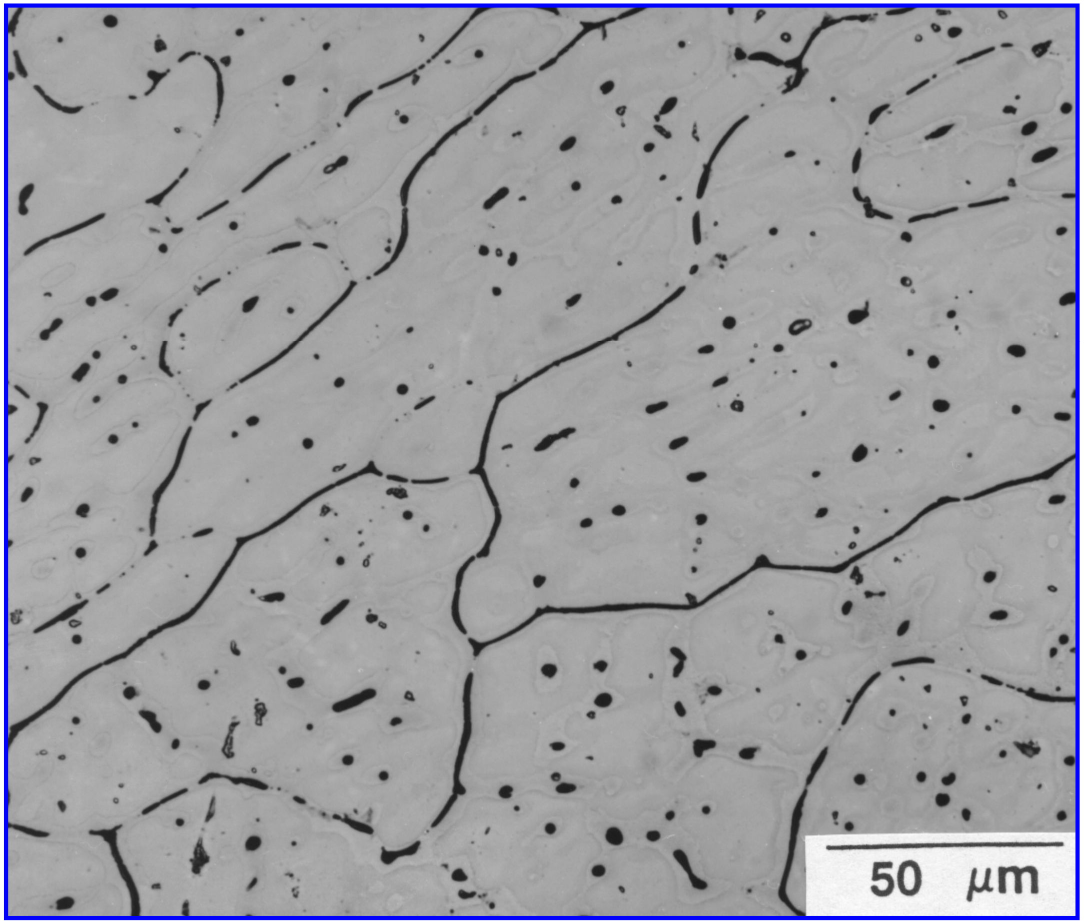


Filler Metal 82 – Nickel-Base Alloy

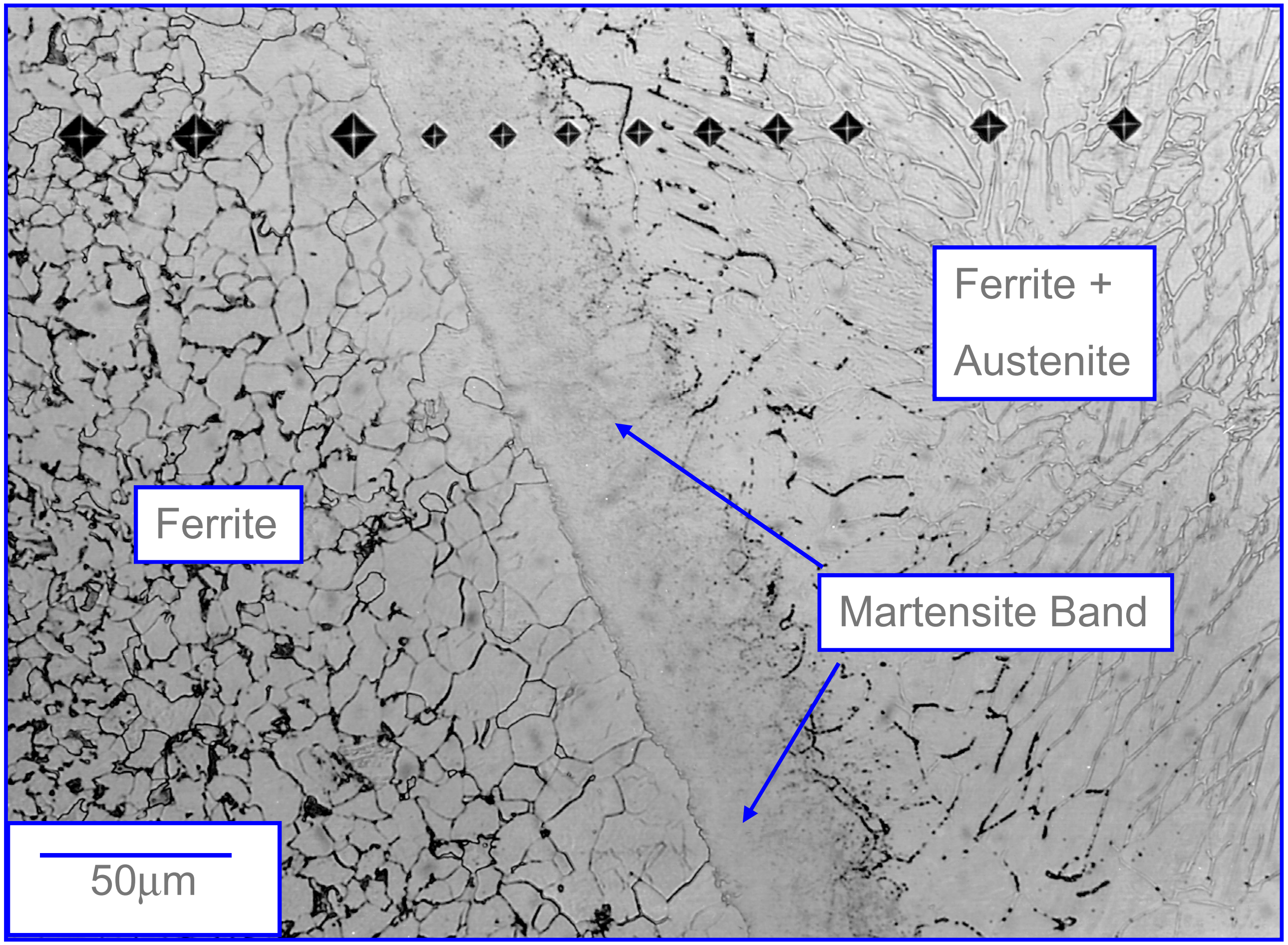


Arrows indicate migrated grain boundaries

Microstructure - Aluminum Alloy

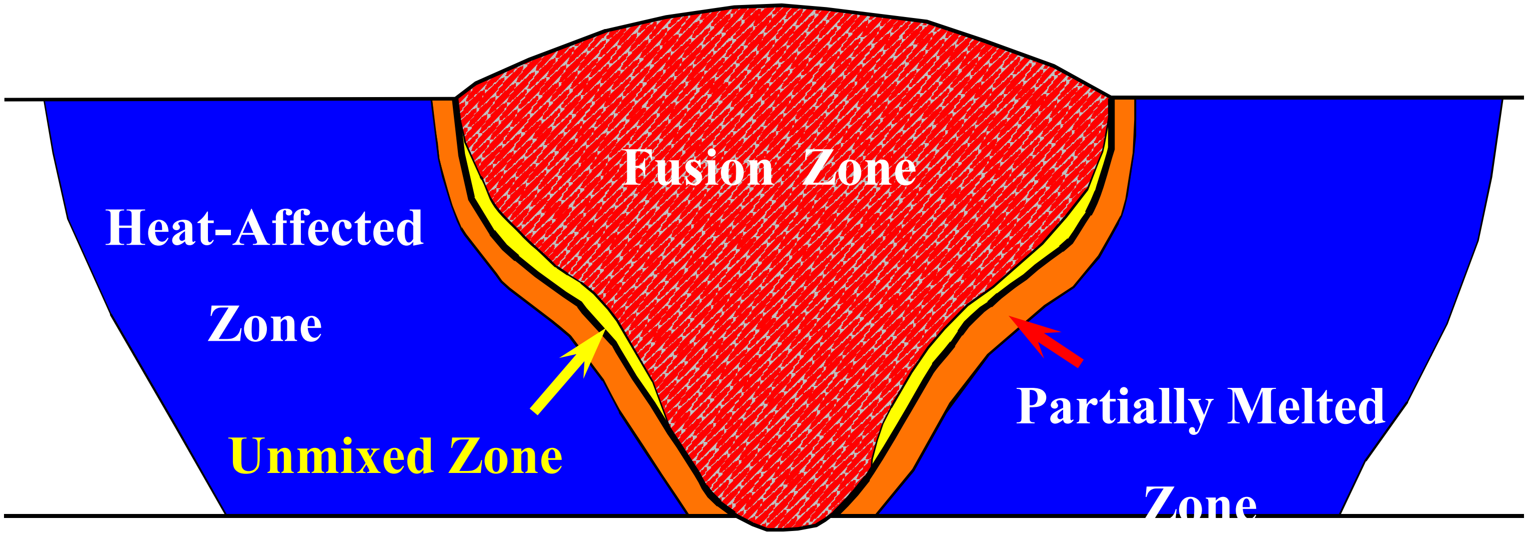


Transition Region



Carbon steel base metal with austenitic stainless steel filler metal

Unmixed Zone (UMZ)



- Narrow region adjacent to the fusion boundary
- Completely melted and resolidified base metal
- No mixing with the bulk fusion zone (composite region)

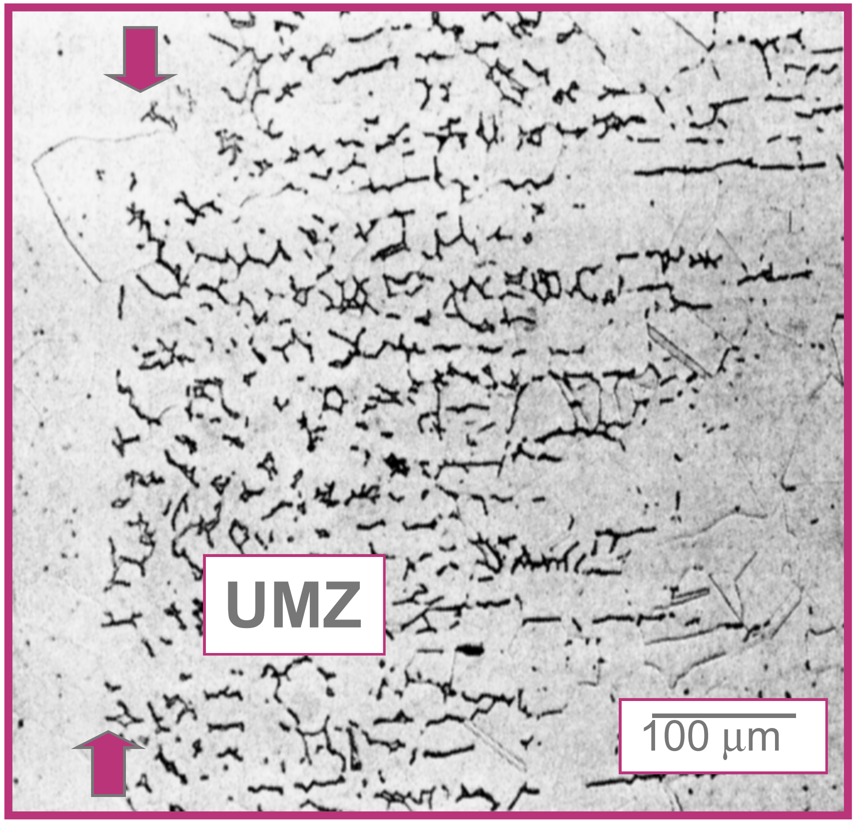
Factors Influencing UMZ Formation

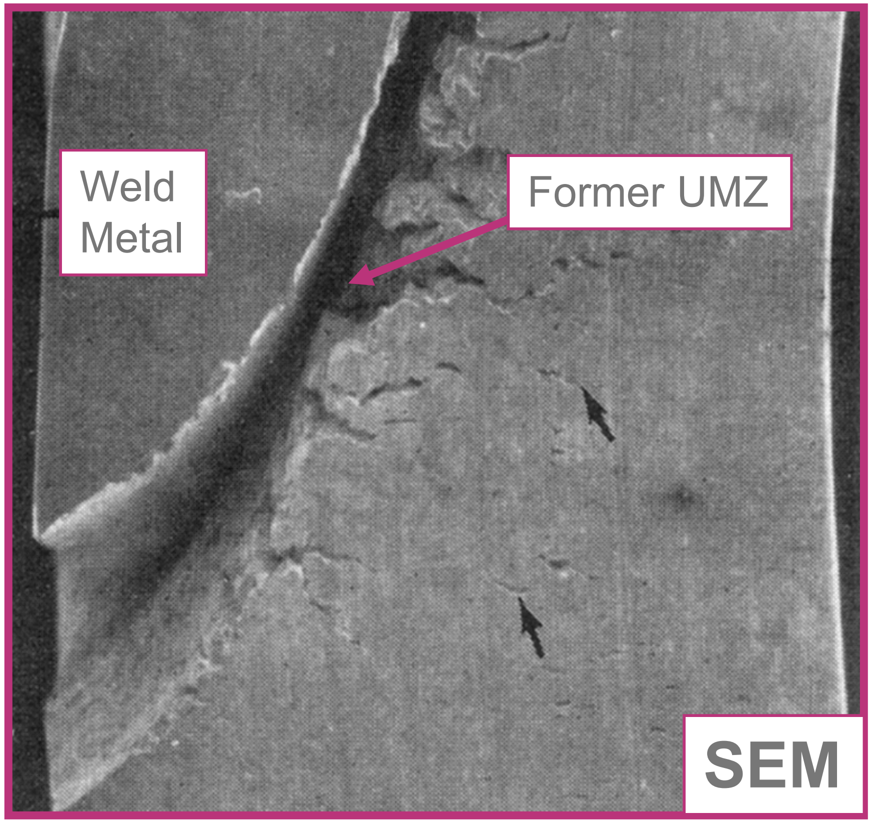
- Base metal/filler metal composition
- Physical properties
  - Melting point
  - Fluid viscosity
  - Miscibility
- Welding process
  - Most prevalent in arc welding processes (GTAW, GMAW)
  - Not observed in EBW and LBW
- Process conditions
  - Heat input
  - Fluid flow

Alloy Systems

Low Alloy Steels	HY-80
Austenitic Stainless Steels	310/304L, 312/304L
Superaustenitic Stainless Steels	AL6XN, 254SMO
Aluminum Alloys	4043/6061, 2319/2195
Nickel-based Alloys	Alloys 600 and 625
Dissimilar combinations	308L/625

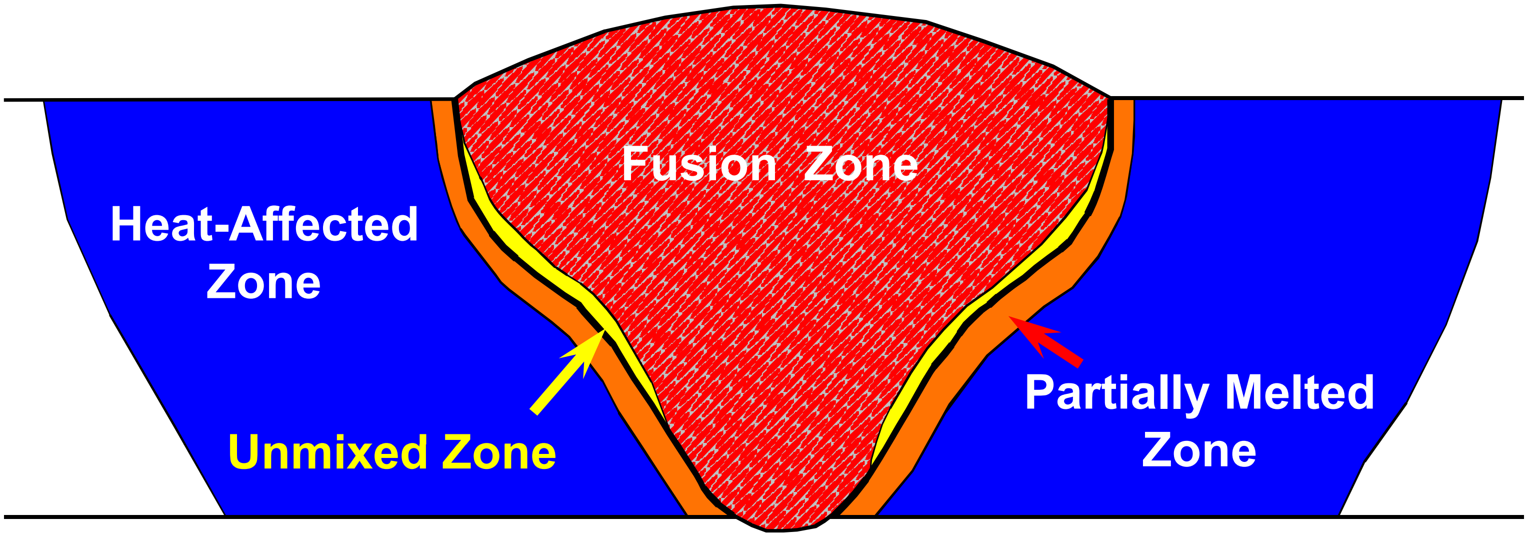
Austenitic Stainless Steels





From Baeslack and Lippold

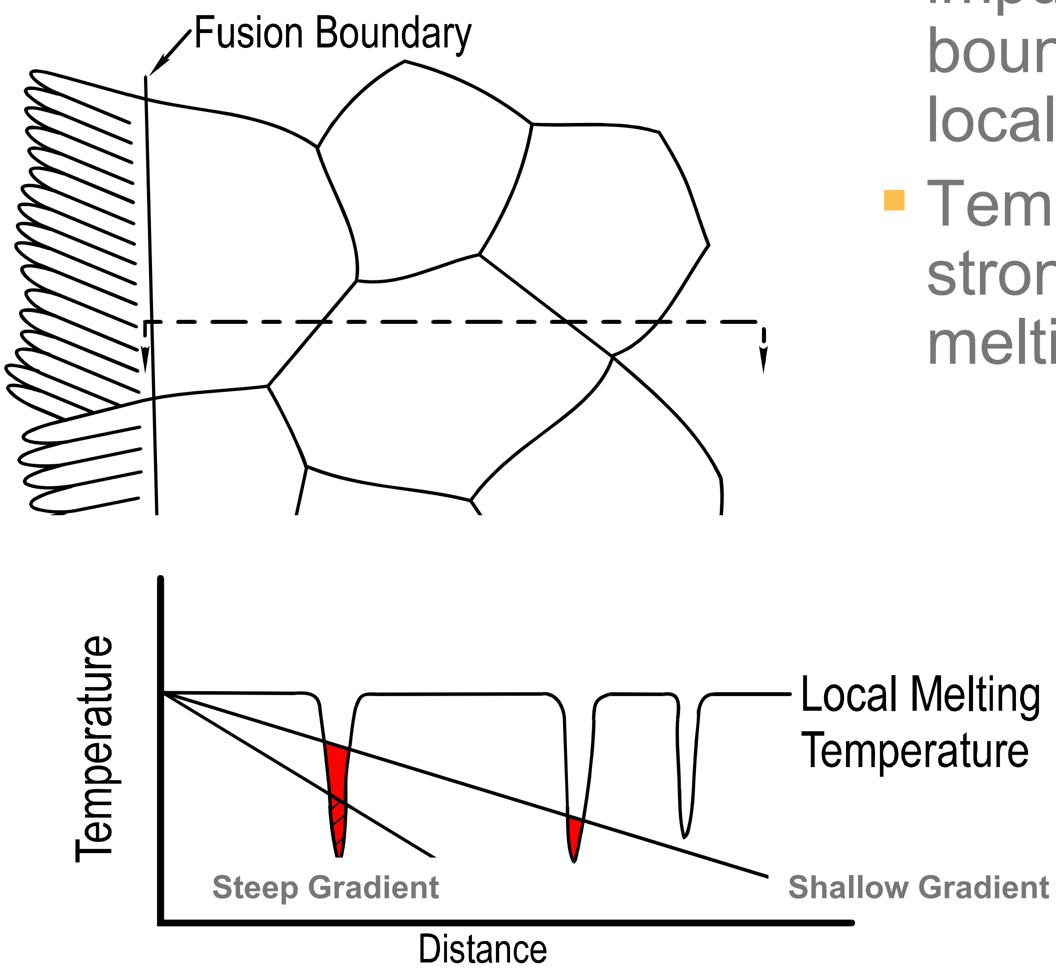
Partially Melted Zone (PMZ)



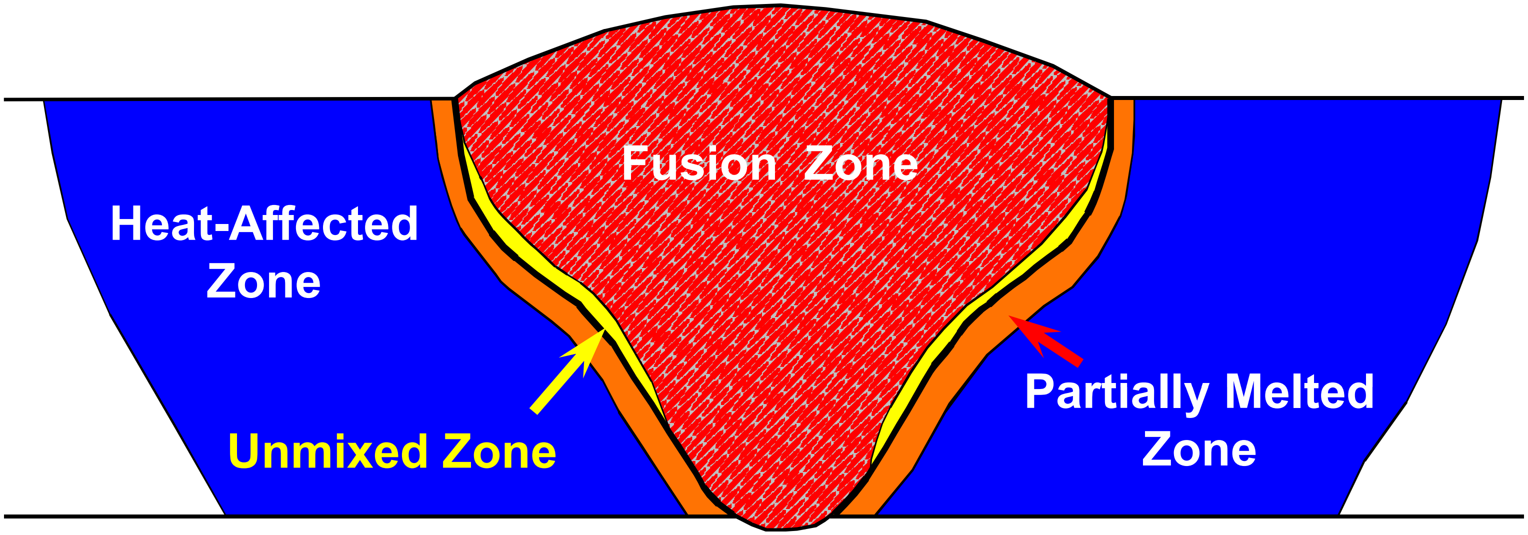
- Region separating the fusion zone from the “true” heat-affected zone
- Transition from 100% liquid at the fusion boundary to 100% solid in the HAZ
- Localized melting normally observed at grain boundaries
- Constitutional liquation of certain particles

Grain Boundary Liquation in the PMZ

- Segregation of solute/ impurities to grain boundaries depresses the local melting point
- Temperature gradient has a strong effect on the extent of melting



The “True” Heat-Affected Zone (HAZ)

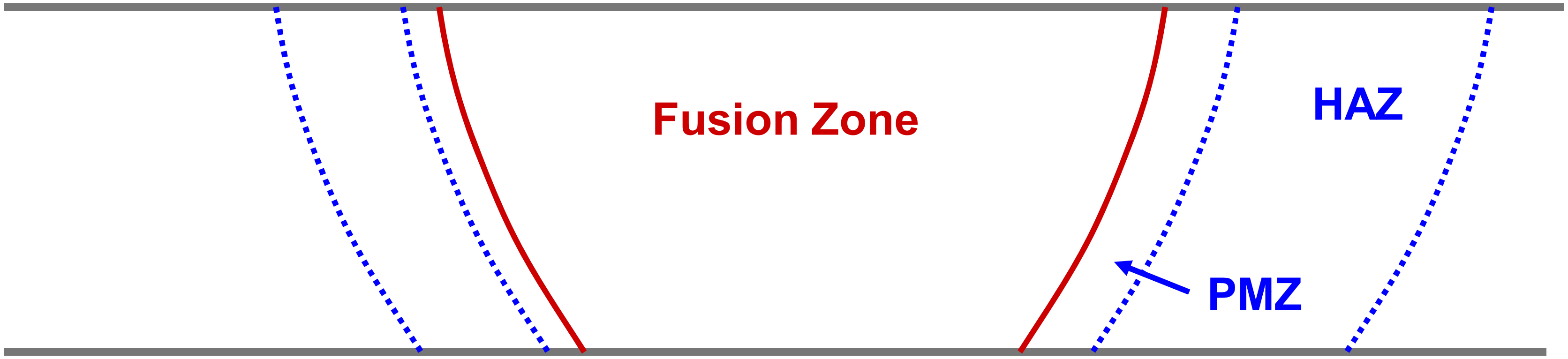


- Adjacent to the PMZ
- All metallurgical reactions occur in the solid state
- Strongly dependent on weld thermal cycle and heat flow conditions

Metallurgical Reactions

- Solid-state metallurgical reactions
  - Recrystallization
  - Grain growth
  - Allotropic / phase transformations
  - Dissolution / overaging of precipitates
  - Formation of precipitates
  - Formation of residual stresses
- Degradation of weldment properties is often associated with the HAZ

Effect of Heat Input and Heat Flow

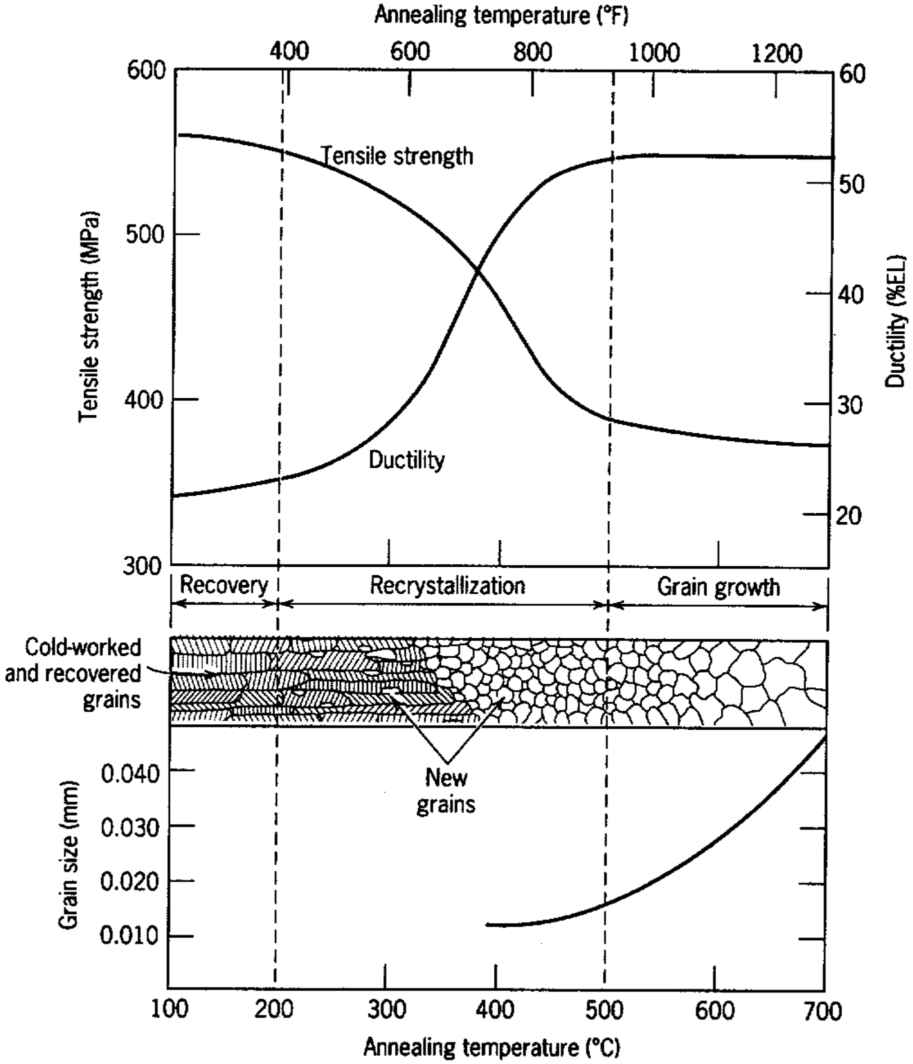


- Low HI
- Effective heat flow

- High HI
- Restricted heat flow

- HAZ width dictated by weld thermal conditions
- HAZ temperature gradient
  - Heat input
  - Heat flow

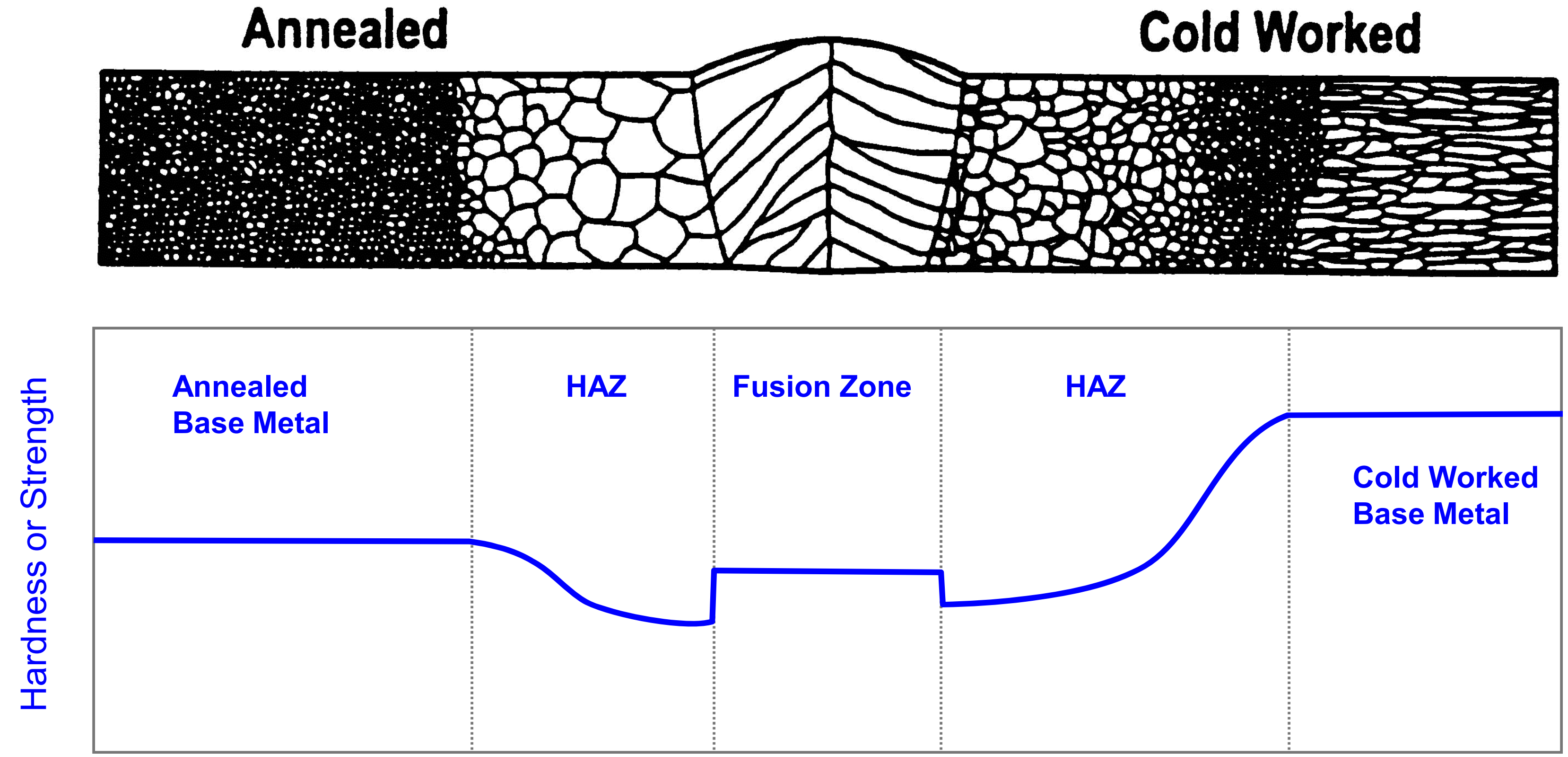
Effect of Recrystallization on Strength and Ductility



From W.D. Callister

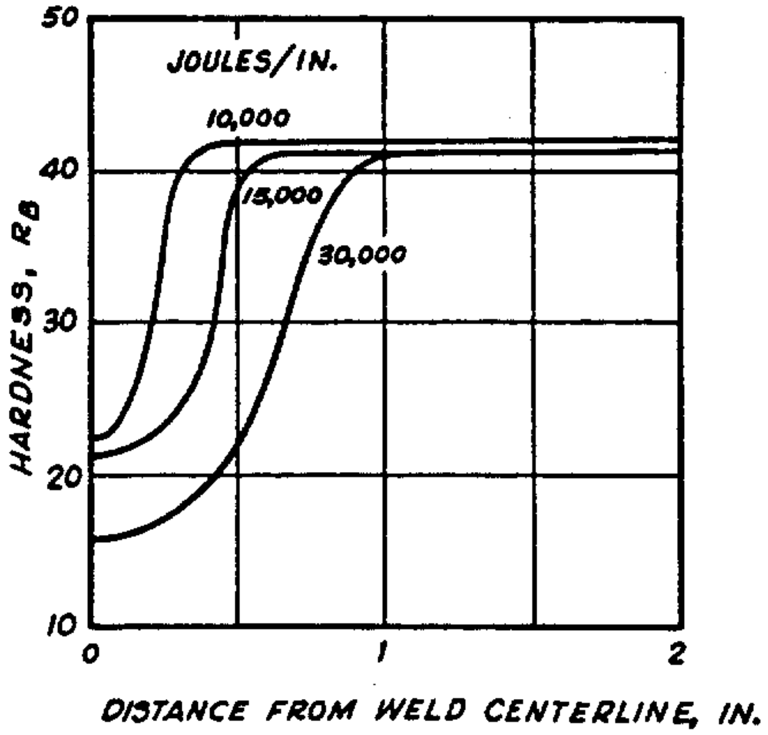
- Recrystallization promotes
  - loss in strength
  - Increase in ductility
- Grain growth promotes some additional softening

Annealed vs. Cold Worked HAZs

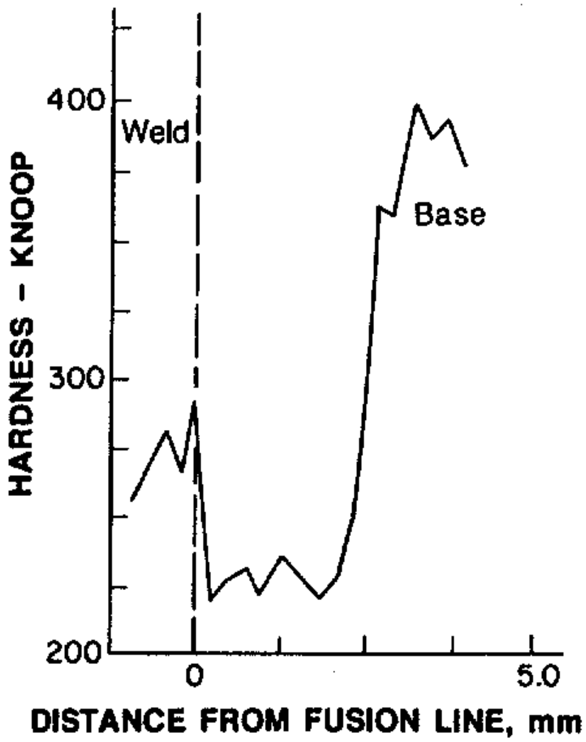


HAZ Softening

Aluminum Alloy 5356-H3



Nickel-base Alloy 718

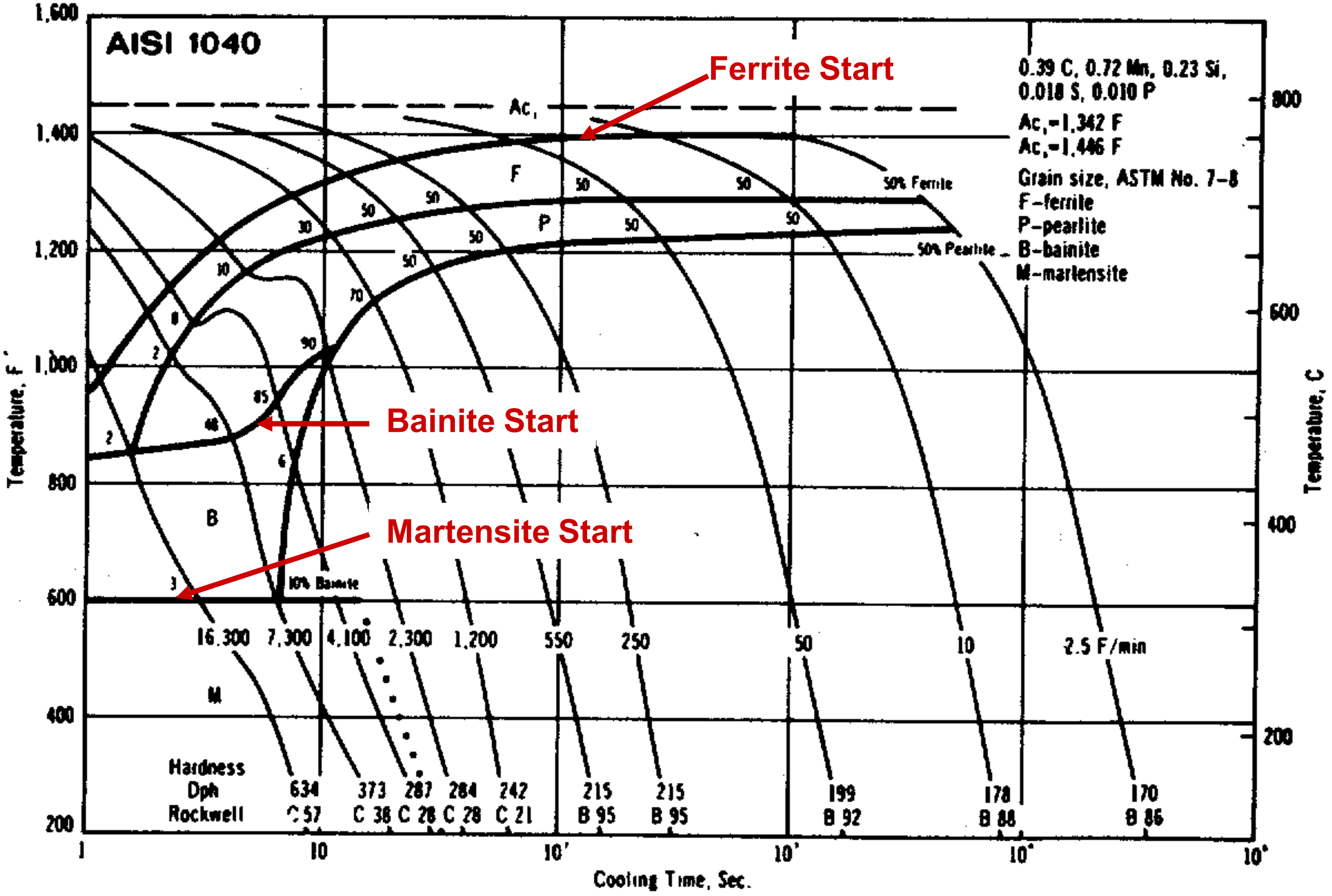


from AWS Handbook

HAZ Transformations in Steels

- Function of composition and cooling rate
- Regions that form austenite during heating transform during cooling
    - Ferrite
    - Pearlite
    - Bainite
    - Martensite
    - Combinations of phases
- CCT diagrams

Continuous Cooling Transformation Diagrams



Ferrite Start

Bainite Start

Martensite Start

Phase Transformations

- Most engineering alloy systems undergo phase transformations in the HAZ
  - Copper alloys, β (BCC) → α (FCC)
  - Stainless steels, δ (BCC) → γ (FCC)
- Nature of transformations
  - Diffusion-controlled
  - Diffusionless, or shear-type
    - Martensitic
    - Massive

HAZ of Non-Fusion Joining Processes

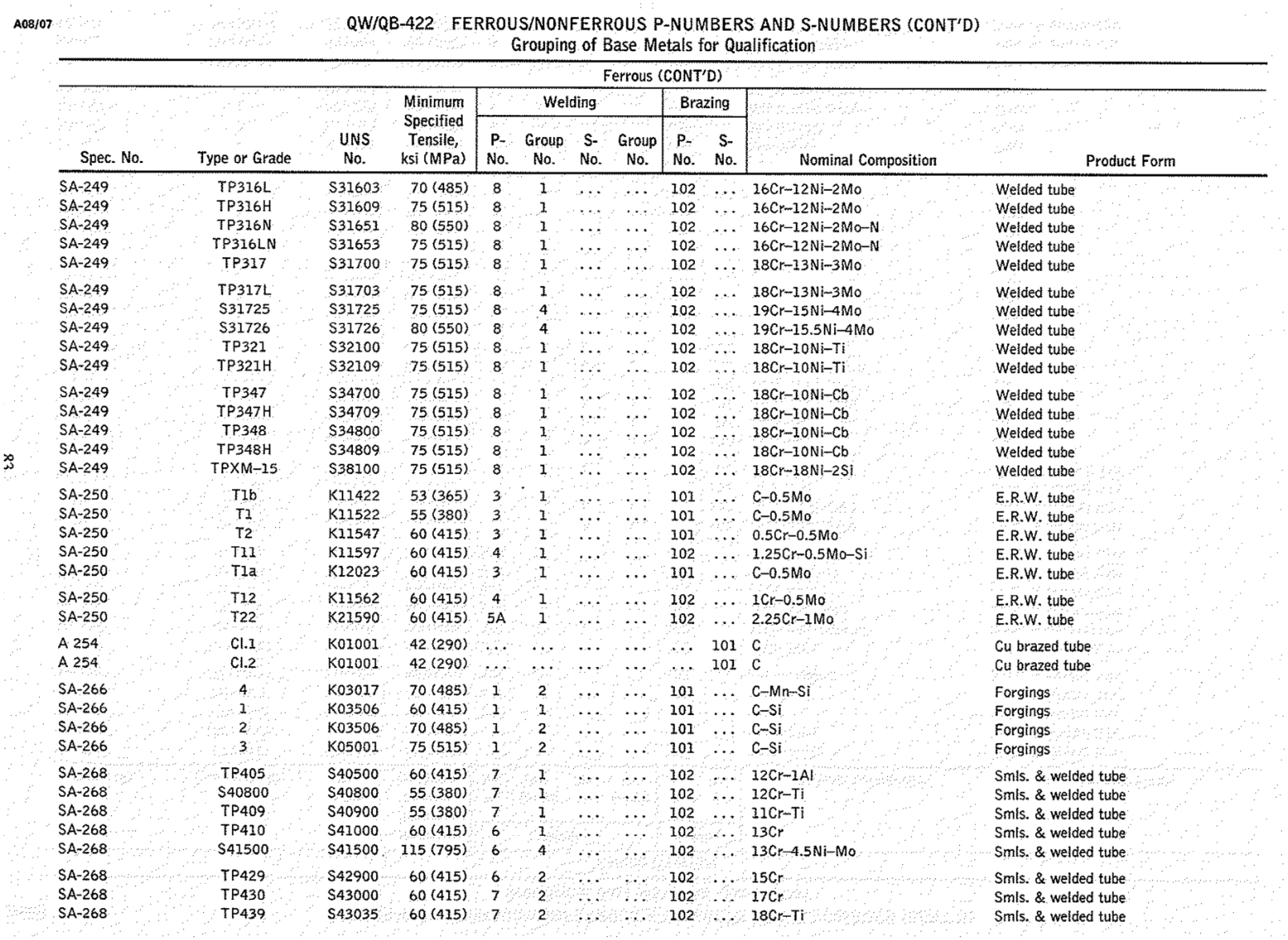
- Solid-state joining processes have no fusion zone but can have a HAZ
  - Friction welding
  - Flash butt welding
  - Diffusion welding
  - Explosion welding
- Friction and flash butt welding
  - Base metal is heated until it is easily deformable
  - Two ends of the joint are forged together
  - Hot base metal is extruded from the joint to form a flash

ASME Section IX – Base Material Variables

- ASME Section IX groups similar materials into P-No. categories
    - Similar composition, weldability and mechanical properties
- In addition to P-No., materials can be further described by Group No., grade, specification, grade, etc.
    - Materials can be specified as P-No.1 Group 1 or P-No.1 Group 2
- P-No. and Group No. are listed in QW/QB 422 of ASME Section IX

- Typically the base material requirements defined by ASME Section IX are independent of the welding process

ASME Section IX – Base Material Variables



A08/07

QW/QB-422 FERROUS/NONFERROUS P-NUMBERS AND S-NUMBERS (CONT'D)

Grouping of Base Metals for Qualification

Ferrous (CONT'D)

Spec. No.	Type or Grade	UNS No.	Minimum Specified Tensile, ksi (MPa)	Welding				Brazing		Nominal Composition	Product Form
				P-No.	Group No.	S-No.	Group No.	P-No.	S-No.		
SA-249	TP316L	S31603	70 (485)	8	1	. . .	. . .	102	. . .	16Cr–12Ni–2Mo	Welded tube
SA-249	TP316H	S31609	75 (515)	8	1	. . .	. . .	102	. . .	16Cr–12Ni–2Mo	Welded tube
SA-249	TP316N	S31651	80 (550)	8	1	. . .	. . .	102	. . .	16Cr–12Ni–2Mo–N	Welded tube
SA-249	TP316LN	S31653	75 (515)	8	1	. . .	. . .	102	. . .	16Cr–12Ni–2Mo–N	Welded tube
SA-249	TP317	S31700	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–13Ni–3Mo	Welded tube
SA-249	TP317L	S31703	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–13Ni–3Mo	Welded tube
SA-249	S31725	S31725	75 (515)	8	4	. . .	. . .	102	. . .	19Cr–15Ni–4Mo	Welded tube
SA-249	S31726	S31726	80 (550)	8	4	. . .	. . .	102	. . .	19Cr–15.5Ni–4Mo	Welded tube
SA-249	TP321	S32100	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–10Ni–Ti	Welded tube
SA-249	TP321H	S32109	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–10Ni–Ti	Welded tube
SA-249	TP347	S34700	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–10Ni–Cb	Welded tube
SA-249	TP347H	S34709	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–10Ni–Cb	Welded tube
SA-249	TP348	S34800	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–10Ni–Cb	Welded tube
SA-249	TP348H	S34809	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–10Ni–Cb	Welded tube
SA-249	TPXM–15	S38100	75 (515)	8	1	. . .	. . .	102	. . .	18Cr–18Ni–2Si	Welded tube
SA-250	T1b	K11422	53 (365)	3	1	. . .	. . .	101	. . .	C–0.5Mo	E.R.W. tube
SA-250	T1	K11522	55 (380)	3	1	. . .	. . .	101	. . .	C–0.5Mo	E.R.W. tube
SA-250	T2	K11547	60 (415)	3	1	. . .	. . .	101	. . .	0.5Cr–0.5Mo	E.R.W. tube
SA-250	T11	K11597	60 (415)	4	1	. . .	. . .	102	. . .	1.25Cr–0.5Mo–Si	E.R.W. tube
SA-250	T1a	K12023	60 (415)	3	1	. . .	. . .	101	. . .	C–0.5Mo	E.R.W. tube
SA-250	T12	K11562	60 (415)	4	1	. . .	. . .	102	. . .	1Cr–0.5Mo	E.R.W. tube
SA-250	T22	K21590	60 (415)	5A	1	. . .	. . .	102	. . .	2.25Cr–1Mo	E.R.W. tube
A 254	Cl.1	K01001	42 (290)	. . .	. . .	. . .	. . .	. . .	101	C	Cu brazed tube
A 254	Cl.2	K01001	42 (290)	. . .	. . .	. . .	. . .	. . .	101	C	Cu brazed tube
SA-266	4	K03017	70 (485)	1	2	. . .	. . .	101	. . .	C–Mn–Si	Forgings
SA-266	1	K03506	60 (415)	1	1	. . .	. . .	101	. . .	C–Si	Forgings
SA-266	2	K03506	70 (485)	1	2	. . .	. . .	101	. . .	C–Si	Forgings
SA-266	3	K05001	75 (515)	1	2	. . .	. . .	101	. . .	C–Si	Forgings
SA-268	TP405	S40500	60 (415)	7	1	. . .	. . .	102	. . .	12Cr–1Al	Smls. & welded tube
SA-268	S40800	S40800	55 (380)	7	1	. . .	. . .	102	. . .	12Cr–Ti	Smls. & welded tube
SA-268	TP409	S40900	55 (380)	7	1	. . .	. . .	102	. . .	11Cr–Ti	Smls. & welded tube
SA-268	TP410	S41000	60 (415)	6	1	. . .	. . .	102	. . .	13Cr	Smls. & welded tube
SA-268	S41500	S41500	115 (795)	6	4	. . .	. . .	102	. . .	13Cr–4.5Ni–Mo	Smls. & welded tube
SA-268	TP429	S42900	60 (415)	6	2	. . .	. . .	102	. . .	15Cr	Smls. & welded tube
SA-268	TP430	S43000	60 (415)	7	2	. . .	. . .	102	. . .	17Cr	Smls. & welded tube
SA-268	TP439	S43035	60 (415)	7	2	. . .	. . .	102	. . .	18Cr–Ti	Smls. & welded tube

ASME Section IX – Base Material Variables

P-No.	Description
1	C, C-Mn, and C-Mn-Si steels
3	Low-alloy steels [Mo, Mn-Mo, Si-Mo and Cr-Mo (Cr ≤ ¾% and total alloy content < 2%)]
4	Cr-Mo low-alloy steels with Cr between ¾% and 2% and total alloy content < 2 ¾%
5A	Cr-Mo low-alloy steels with Cr ≤ 3% and < 85 ksi minimum tensile strength
5B	Cr-Mo low-alloy steels with Cr > 3% and ≤ 85 ksi minimum tensile strength
5C	Cr-Mo low-alloy steels with Cr between 2 ¼ % and 3% and ≥ 85 ksi minimum tensile strength
6	Martensitic stainless steels
7	Ferritic stainless steels - nonhardneable
8	Austenitic stainless steels

ASME Section IX – Base Material Variables

P-No.	Description
9A, 9B, 9C	Nickel alloy steels with 4.5% Ni
10A – 10K	Mn-V and Cr-V steels, 26% Cr-3% Ni-3% Mo, and 29% Cr-4% Mo-2% Ni steels and duplex stainless steels
11A, 11B	Low-alloy quench and tempered steels with > 95 ksi minimum tensile strength
21 – 25	Aluminum and aluminum-base alloys
31 – 35	Copper and copper-base alloys
41 – 47	Nickel and nickel-base alloys
51 – 53	Titanium and titanium-base alloys
61, 62	Zirconium and zirconium-base alloys

ASME Section IX – Base Material Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-402 Joint	.3	Φ Backing Composition			X
QW-403 Base Material	.1	φ P-No. Qualified	X		
	.4	φ Group Number		X	
	.5	φ Group Number		X	
	.11	φ P-No. Qualified	X		
	.12	φ P-No./Melt-in	X		
	.15	φ P-No. Qualified	X		
	.17	φ Base Metal or Stud Metal P-No.	X		
	.19	φ Base Metal	X		
	.24	φ Specification, Type, or Grade	X		

Carbon and Low Alloy Steels

Module 3C

Classification by Composition

- Plain carbon
  - **Low carbon, < 0.2 wt%**
  - **Medium carbon, 0.2-0.6 wt%**
  - **High carbon, 0.6-1.0 wt%**
  - **Ultrahigh carbon, 1.25-2.0 wt%**
- Low alloy, up to 8% alloying addition
  - **Low carbon, quench and tempered**
  - **Medium carbon, ultrahigh strength**
  - **Cr-Mo heat resistant**
- High strength, low alloy (HSLA)
  - **Micro-alloyed**
  - **Dual-phase**
  - **Control-rolled**
  - **Weathering**
  - **Pearlite-reduced**
  - **Acicular ferrite**
- High alloy, > 8% alloy addition
  - **High Cr, heat-resistant**
  - **Stainless**

Steel Classification Systems

- AISI/SAE

1020

- 1 = carbon steel
- 0 = plain carbon steel
- 20 = 20/100 % carbon

4340

- 4 = molybdenum steel
- 3 = Ni-Cr-Mo (1.8% Ni)
- 40 = 40 / 100 % carbon

- ASTM

A516

- C-steel pressure vessel plates
- Graded by tensile strength

- ASME Boiler and Pressure Vessel Code

P1

- P groups of similar steel
- Simplified qualification

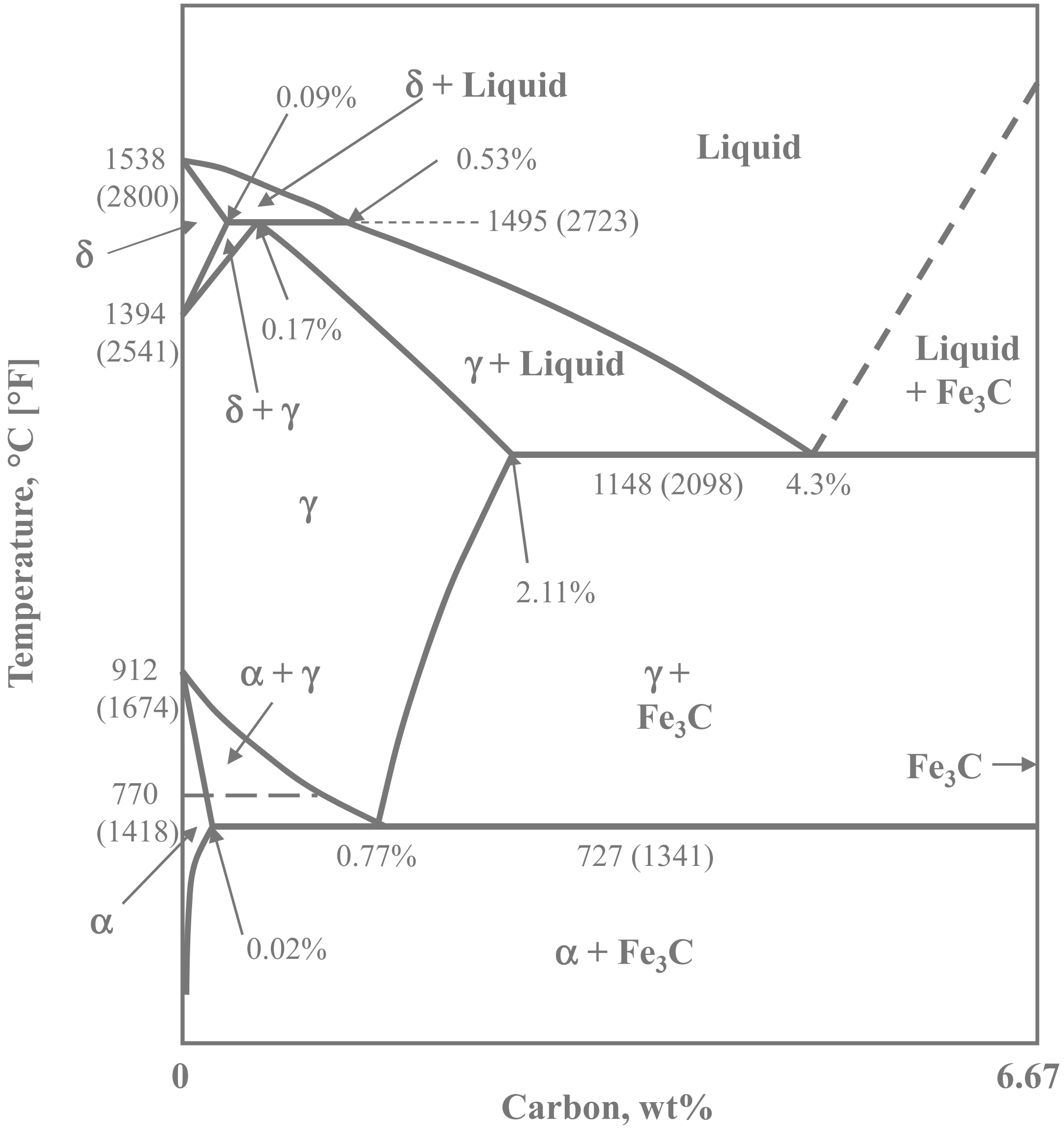
Carbon Steels Used in the Nuclear Industry

Designation	Composition (wt%)	Mechanical Properties	Uses
SA-36	0.2C, 0.15-0.4Si, 0.8-1.2Mn	UTS: 58-80 ksi YS: 36 ksi min. Elong: 20% min.	General structural
SA508, Class 3	0.2C, 0.15-0.40Si, 1.2-1.5Mn, 0.4-1.0Ni, 0.45-0.6Mo	UTS: 90-115 ksi YS: 65 ksi min Elong: 16% min.	Quench and tempered forgings for pressure vessels
SA-533, Type C	0.25C, 0.15-0.40Si, 1.15-1.5Mn, 0.4-0.7Ni, 0.45-0.6Mo	UTS: 100-125 ksi YS: 83 ksi min. Elong: 16% min.	Quench and tempered steel plates for pressure vessels

Different Phases in Steel

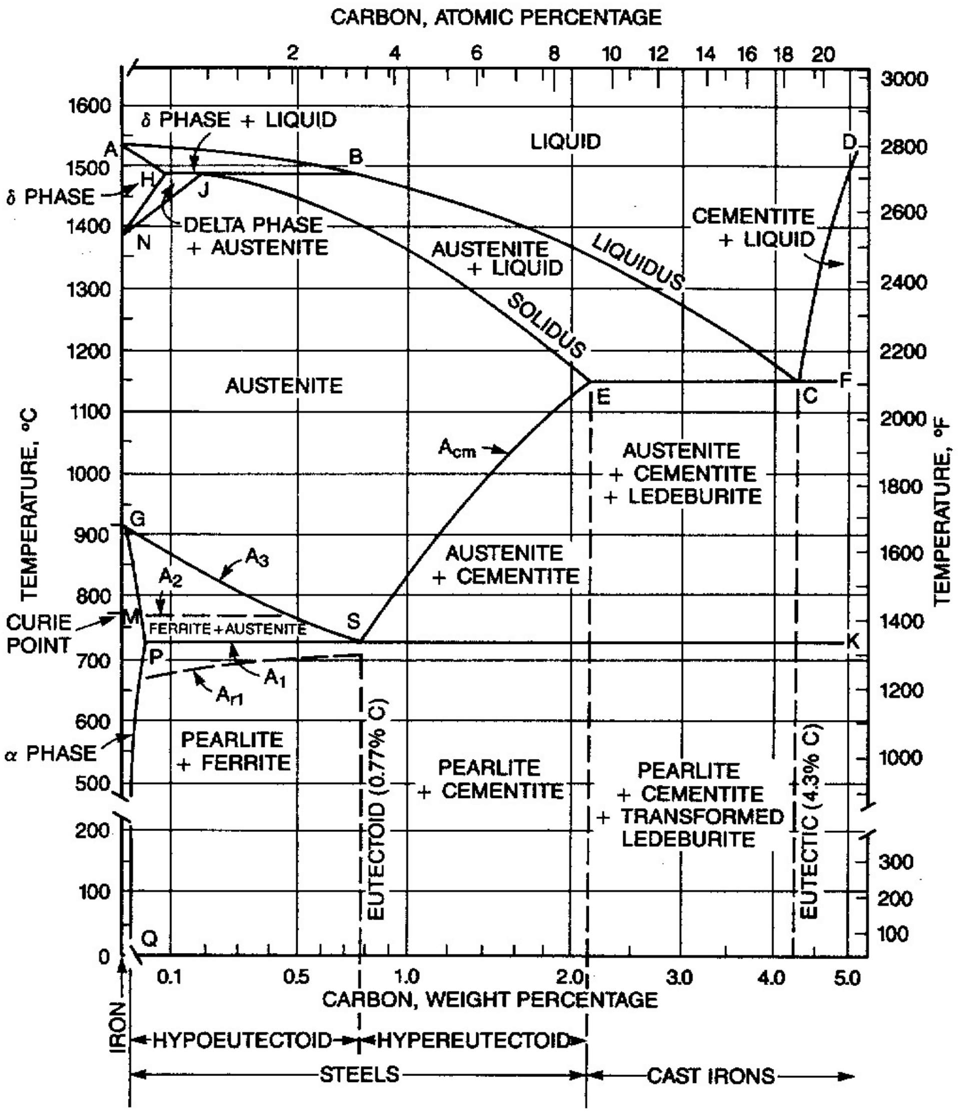
- Iron can exhibits 3 separate solid phases between room temperature and its melting temperature
  - Low temperature ferrite (bcc) – alpha ferrite
  - Austenite (fcc)
  - High temperature ferrite (bcc) – delta ferrite
- When carbon is added to iron to form steel, another phase known as cementite (Fe_3C) can form
- Steels are known as “allotropic” materials because the same composition can have different phases depending on temperature

Iron-Iron Carbide Phase Diagram



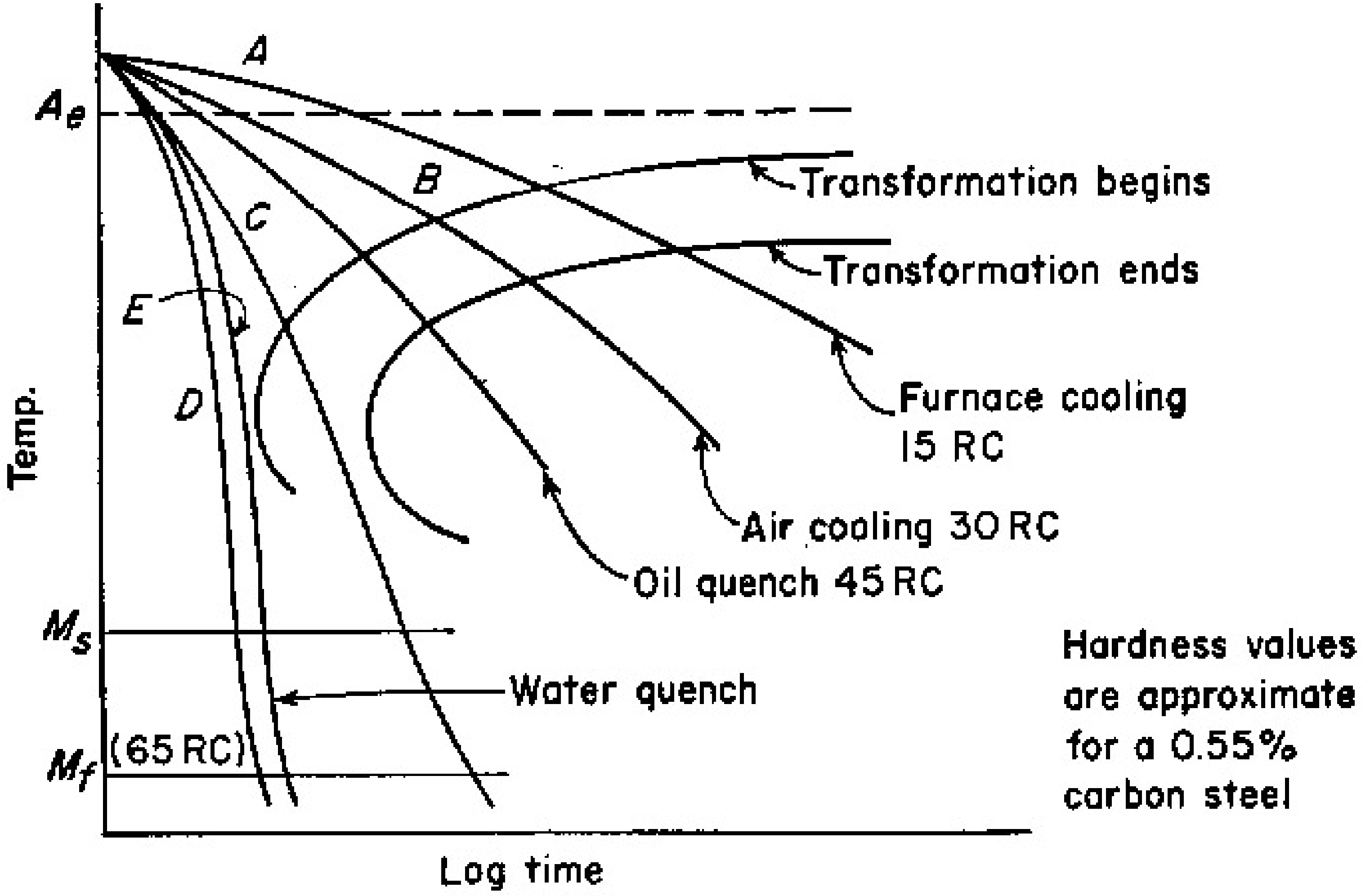
- Iron-rich end of Fe-C equilibrium phase diagram
- Equilibrium phases
  - Ferrite (alpha and delta)
  - Austenite
  - Cementite (Fe_3C)
- Invariant reactions
  - Peritectic (1495°C, 0.17%C)
  - Eutectic (1148°C, 4.3%C)
  - Eutectoid (727°C, 0.77%C)

Iron-Iron Carbide Phase Diagram

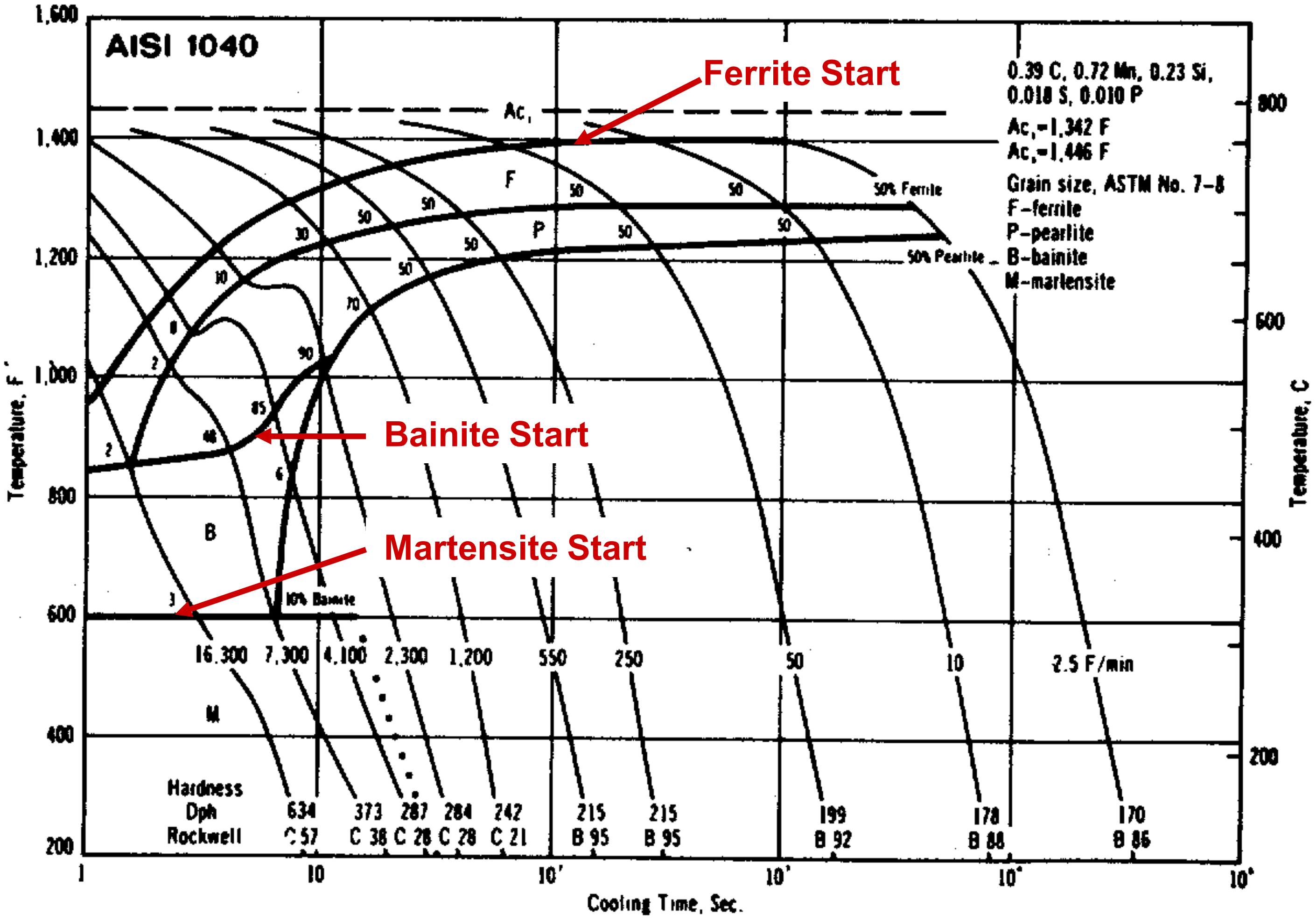


- Steels
  - C content generally less than 1.0 wt%
  - Hypoeutectoid – less than 0.77% carbon
  - Hypereutectoid – between 0.77 and 2.1% C
- Cast irons
  - Greater than 2.1% carbon
  - High volume fraction cementite

Continuous Cooling Transformation Diagram



Continuous Cooling Transformation Diagrams

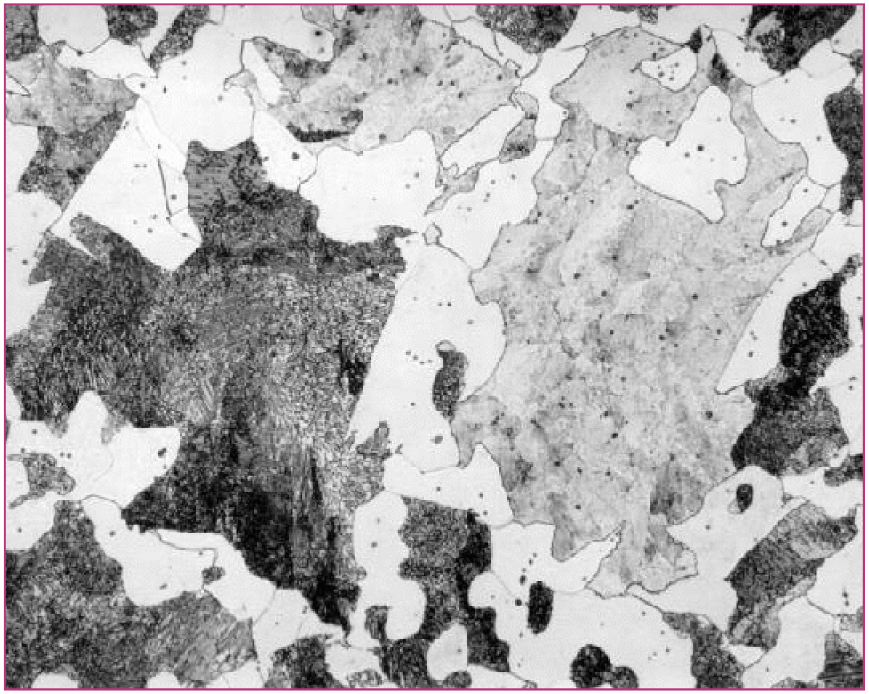


Ferrite Start

Bainite Start

Martensite Start

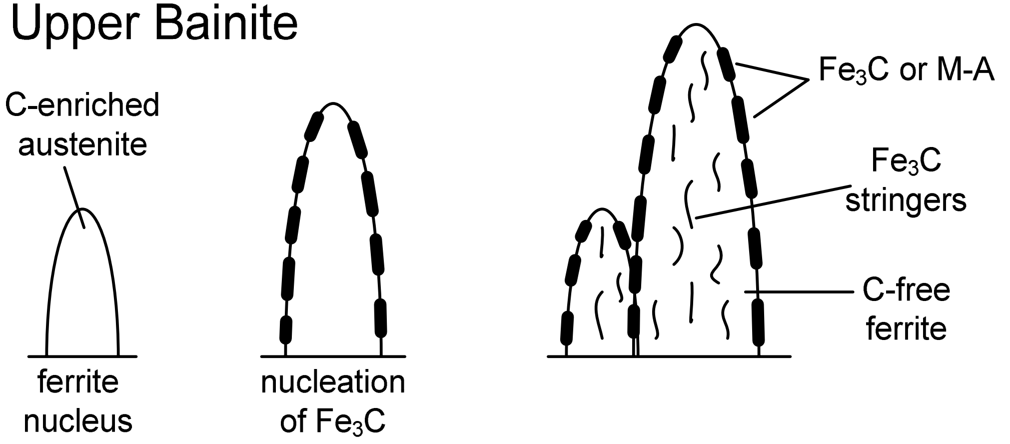
Slow Cooling → Ferrite + Pearlite



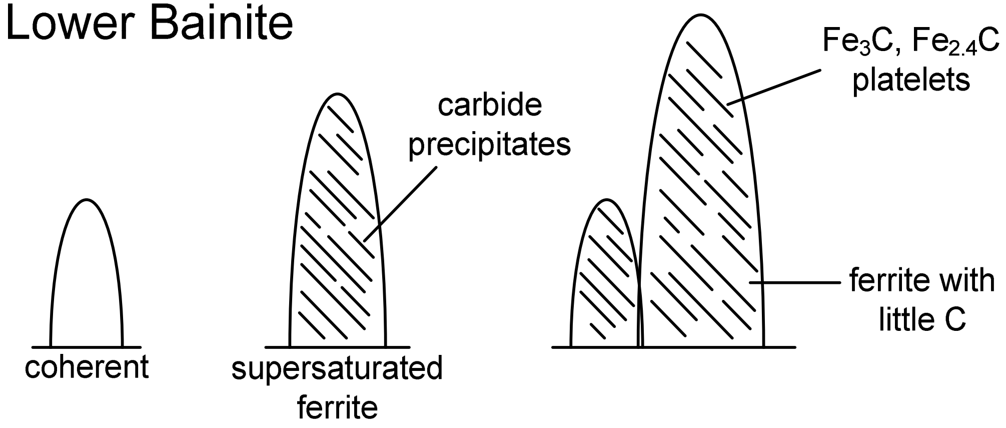
- Ferrite is a soft and ductile phase found in steel microstructures
  - Ferrite can contain £ 0.025% carbon
- Pearlite is a banded mixture of ferrite and cementite (Fe_3C)
  - Cementite contains the excess carbon that the ferrite can't hold

Bainite

Upper Bainite



Lower Bainite



- Medium/high cooling rates
- Suppressed proeutectoid and eutectoid transformations
- Undercooled austenite
- Short range diffusion of carbon
- Precipitation of Fe_3C and carbides
- Formation of bainitic ferrite
- Low toughness of upper bainite

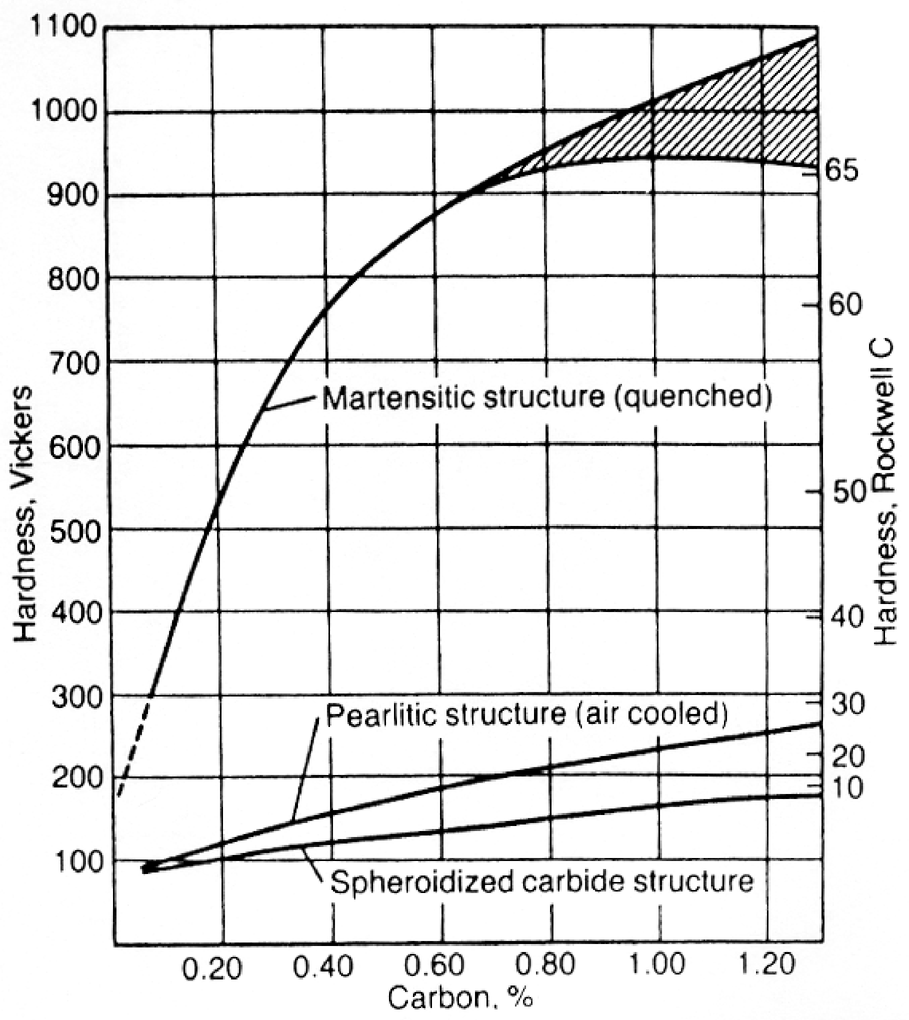
Fast Cooling → Martensite

- Martensite is very strong, hard, and brittle
- Body centered tetragonal crystal structure (bct)
- High dislocation density
- Metastable structure

Martensite: Good or Bad?

- **GOOD** Aspects of Martensite
  - High strength and hardness compared to ferrite + pearlite
  - Many steels are designed to be quenched to form martensite then tempered to improve their ductility and toughness
    - 4130
    - 4340
- **BAD** Aspects of Martensite
  - Martensite results in low ductility and toughness
  - Increases the possibility of hydrogen induced cracking (HIC) particularly in highly restrained joints

Hardness - Effect of Carbon



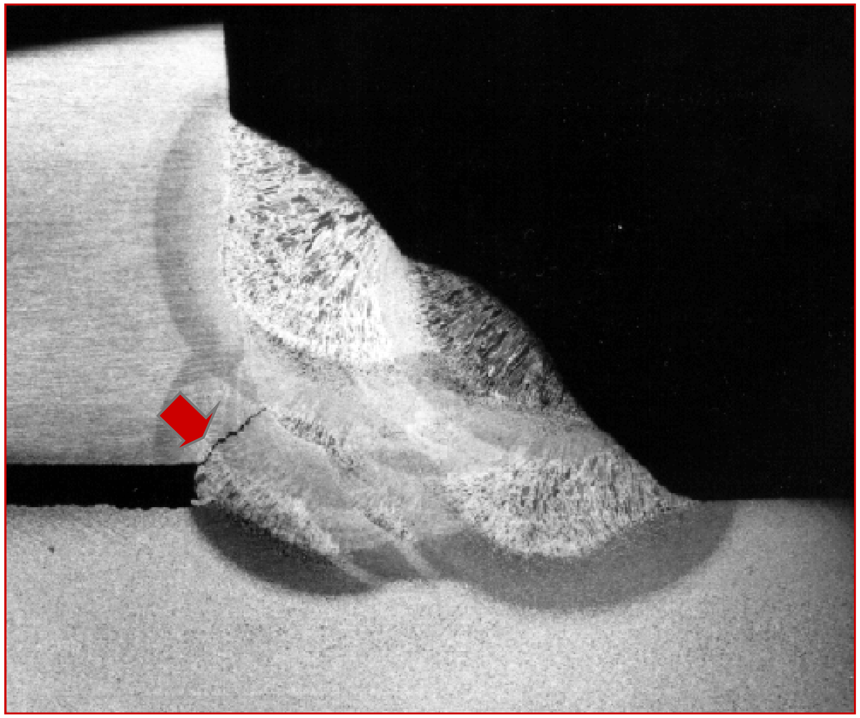
- Carbon is the most important alloying element in steel
- Interstitial element
- Forms carbides with Fe and other alloying elements (Cr, Mo, V)
- Greatly facilitates transformation hardening
- Controls the maximum hardness achievable in the alloy

Hardness versus Hardenability

- Hardenability is the ease with which hardening occurs upon cooling from the austenite phase field
- Associated with the formation of martensite
- Factors which influence hardenability
  - Carbon content
  - Alloying additions
  - Prior austenite grain size
  - Homogeneity of the austenite
  - Section thickness

Hydrogen Induced Cracking and Martensite

- Four factors are required for hydrogen cracking
  - Susceptible microstructure
  - Source of hydrogen
    - Moisture in flux
    - Grease/oil on plates
  - Stress
    - Residual
    - Applied
  - Temperature between -100 and 200°C (-150 and 390°F)

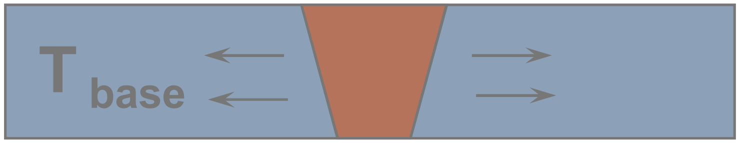


Hydrogen crack at root of multipass weld

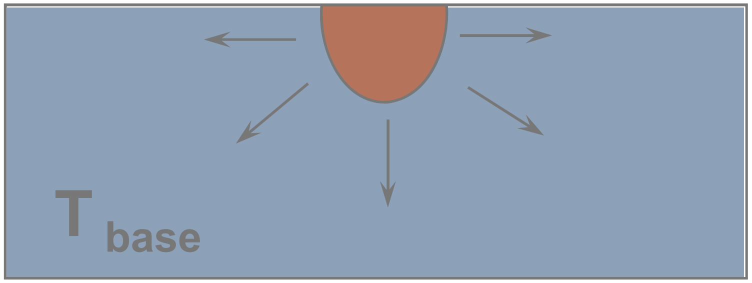
- **Eliminate only one factor and HIC goes away!!**

Using Preheat to Avoid Hydrogen Cracking

- If the base material is preheated, heat flows more slowly out of the weld region
    - Slower cooling rates avoid martensite formation
- Preheat allows hydrogen to diffuse from the metal



Cooling rate $\propto$ $(T - T_{base})^3$



Cooling rate $\propto$ $(T - T_{base})^2$

Interaction of Preheat and Composition

$$\mathrm{CE} = \%\mathrm{C} + \%\mathrm{Mn}/6 + \%(\mathrm{Cr}+\mathrm{Mo}+\mathrm{V})/5 + \%(\mathrm{Si}+\mathrm{Ni}+\mathrm{Cu})/15$$

- Carbon equivalent (CE) measures potential to form martensite, which is generally necessary for hydrogen cracking

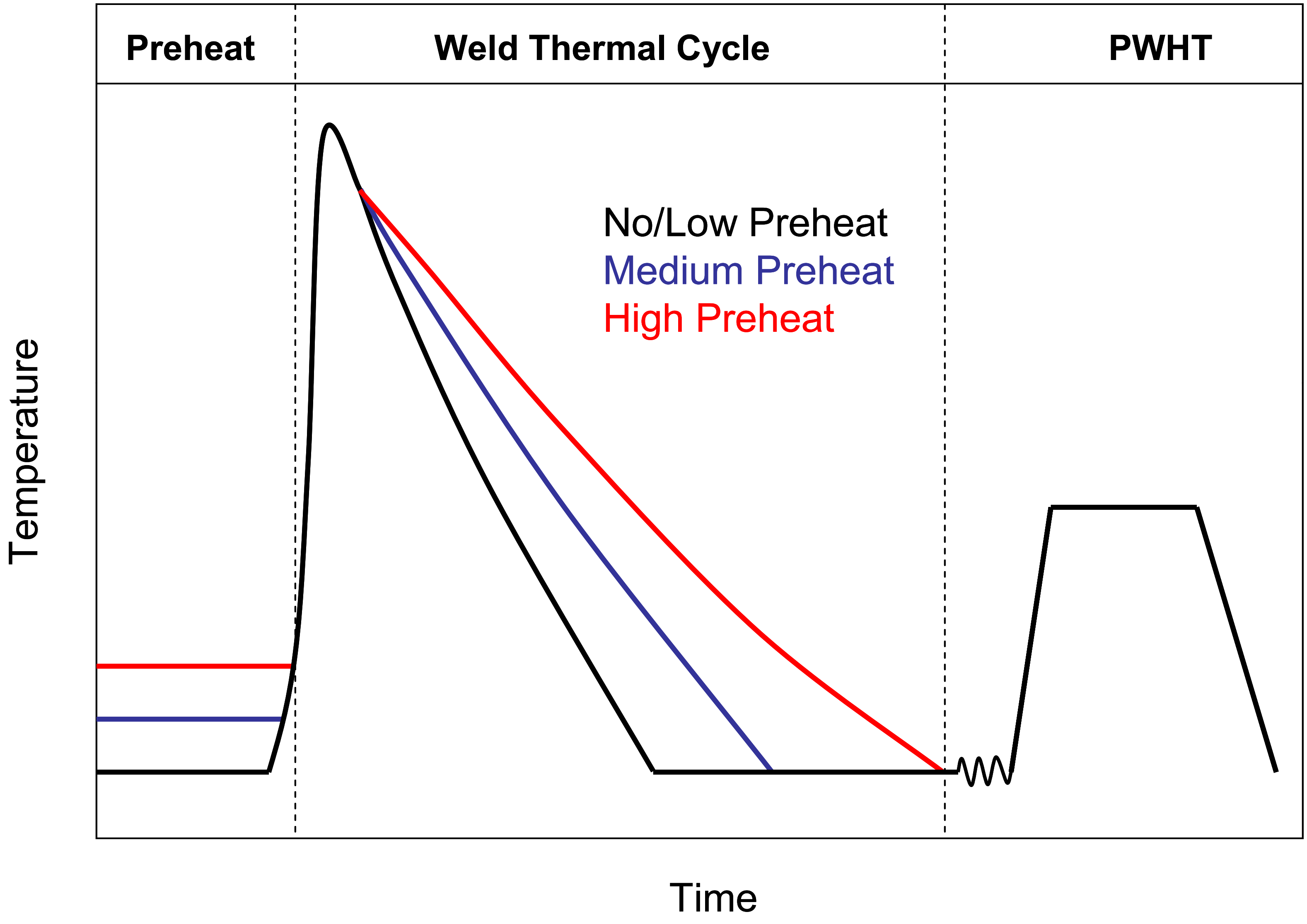
$\mathrm{CE} < 0.35$	no preheat or PWHT
$0.35 < \mathrm{CE} < 0.55$	preheat
$0.55 < \mathrm{CE}$	preheat and PWHT

- Preheat temperature ↑ as CE ↑ and plate thickness ↑

Postweld Heat Treatment and Hydrogen Cracking

- Postweld heat treatment (1100-1250°F) tempers any martensite that may have formed
  - Increase in ductility and toughness
  - Reduction in strength and hardness
- Residual stress is decreased by postweld heat treatment
- Rule of thumb: hold at temperature for 1 hour per inch of plate thickness; minimum hold of 30 minutes
- Postweld heat treatment temperatures vary for different steels
- In general, PWHT for tempering must be done below the lower critical (A_1) temperature

Preheat and PWHT



Welding Consumables for Carbon Steels

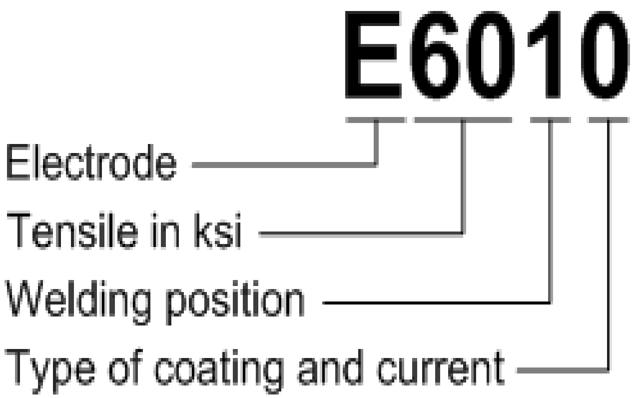
- Processes used in the Nuclear Industry for Primary Fabrication and Repair
  - Shielded Metal Arc Welding (SMAW)
  - Gas Metal Arc Welding (GMAW)
  - Gas Tungsten Arc Welding (GTAW)
  - Flux Cored Arc Welding (FCAW)

AWS Standards Specific to SMAW

- AWS A5.1 - Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding
- AWS A5.5 - Specification for Low-Alloy Electrodes for Shielded Metal Arc Welding
- AWS A5.4 - Specification for Corrosion-Resisting Chromium- and Chromium-Nickel Steels for Shielded Metal Arc Welding

SMAW Electrode Designation

AWS A5.1



E6010

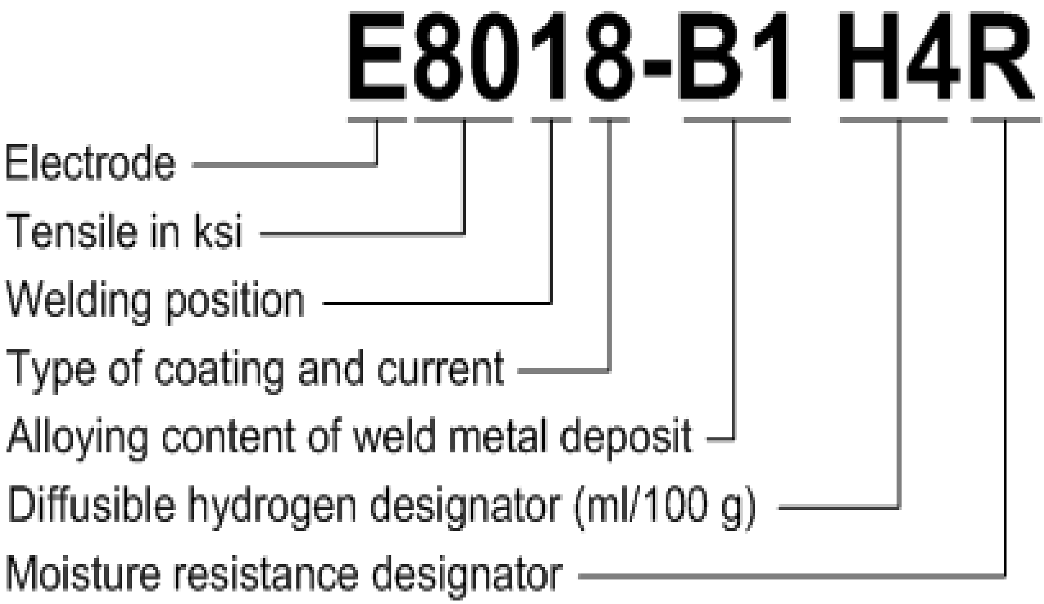
Electrode

Tensile in ksi

Welding position

Type of coating and current

AWS A5.5



E8018-B1 H4R

Electrode

Tensile in ksi

Welding position

Type of coating and current

Alloying content of weld metal deposit

Diffusible hydrogen designator (ml/100 g)

Moisture resistance designator

Welding Position

Digit	Position
1	Flat, Horizontal, Vertical, Overhead
2	Flat and Horizontal only
3	Flat only
4	Flat, Horizontal, Vertical Down, Overhead

SMAW Electrode Designation

Type of Coating and Current

Digit	Type of Coating	Current
0	Cellulose sodium	DC+
1	Cellulose potassium	AC, DC±
2	Titania sodium	AC, DC-
3	Titania potassium	AC, DC+
4	Iron powder titania	AC, DC±
5	Low hydrogen sodium	DC+
6	Low hydrogen potassinm	AC, DC+
7	Iron powder iron oxide	AC, DC±
8	Iron powder low hydrogen	AC, DC±

Alloying Content of Weld Metal Deposit

Suffix	%Mn	%Ni	%Cr	%Mo	%V
A1				0.50	
B1			0.50	0.50	
B2			1.25	0.50	
B3			2.25	1.00	
C1		2.50			
C2		3.25			
C3		1.00	0.15	0.35	
D1/D2	1.25-2.00			0.25-0.45	
G(1)		0.50	0.30 min.	0.20 min.	0.10 min.

Examples

E6010	Cellulosic, all position, DCEP, 60 ksi min UTS
E7018	Low hydrogen, all position, AC or DCEP, 70 ksi min UTS
E7010-A	Cellulosic, all position, DCEP, 70 ksi min, carbon/moly

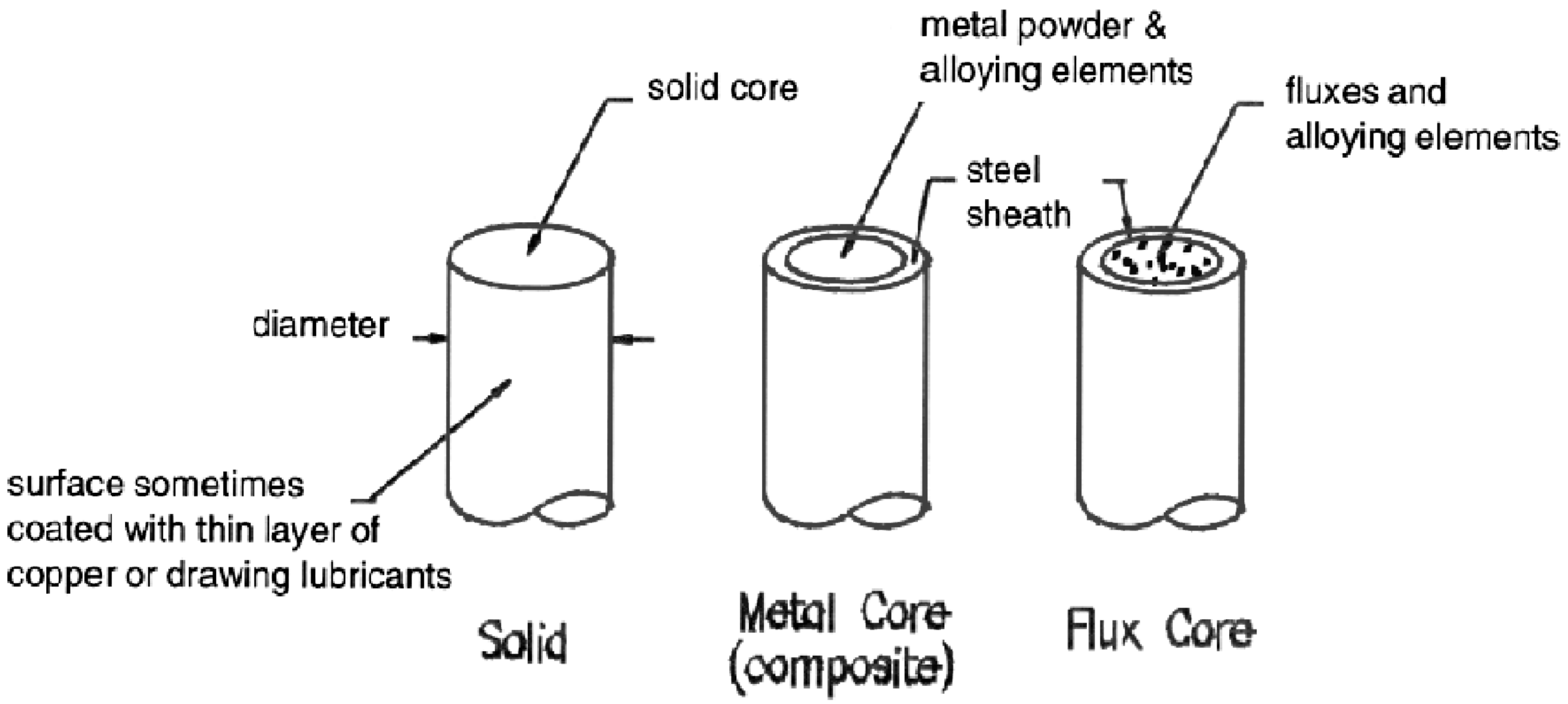
Common SMAW Electrode Coating Descriptions

- XX10- High cellulose sodium, DCEP
- XX11- High cellulose potassium, AC or DCEP

- XX12- Rutile sodium AC, DCEP, DCEN
- XX13- Rutile potassium AC, DCEP, DCEN
- XX14- Rutile + Fe – powder additions AC, DCEP, DCEN

- XX15- Low hydrogen, sodium, DCEP
- XX16- Low hydrogen potassium AC, DCEP
- XX18- Low hydrogen, Fe powder additions AC, DCEP

Types of Continuous Wire Electrodes

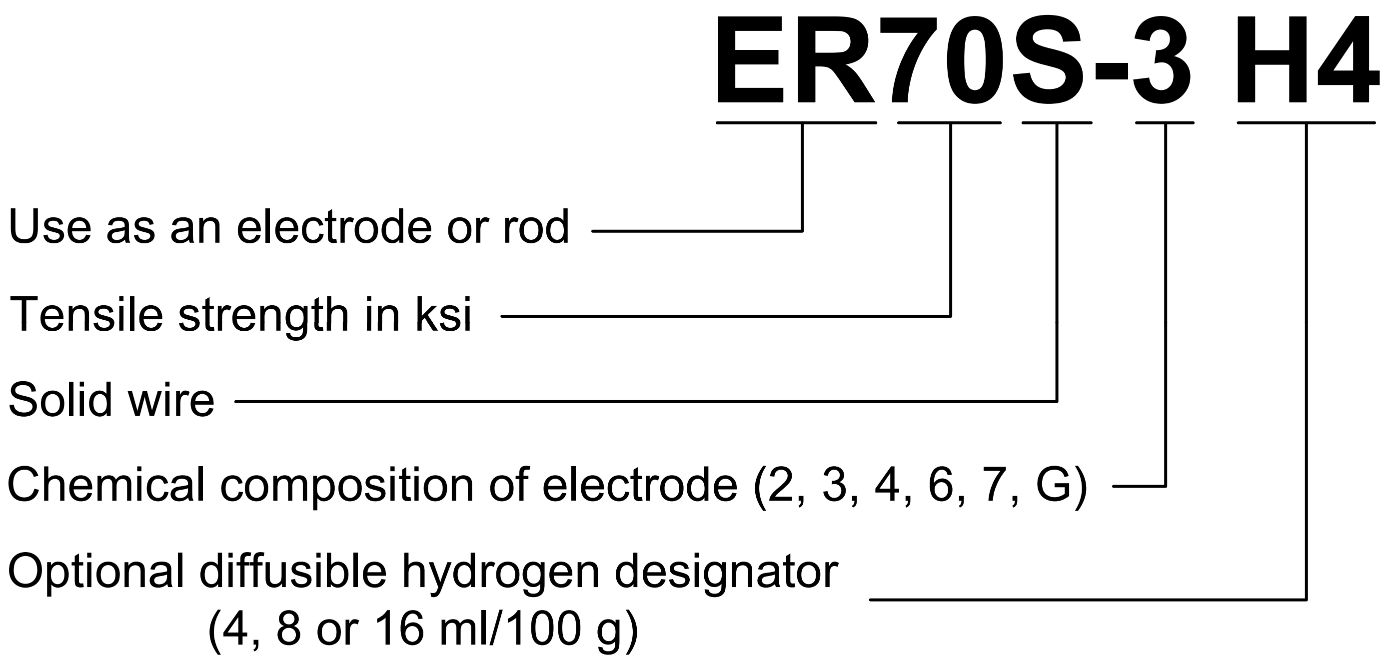


AWS Standards Specific to GTAW and GMAW Electrodes

- AWS A5.18 - Specification for Carbon Steel Electrodes for Gas Shielded Arc Welding
- AWS A5.28 - Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding
- AWS A5.9 - Specification for Stainless Steel Electrodes and Rods for Gas Shielded Arc Welding

AWS Classification for Solid Steel Wires

AWS A5.18



ER70S-3 H4

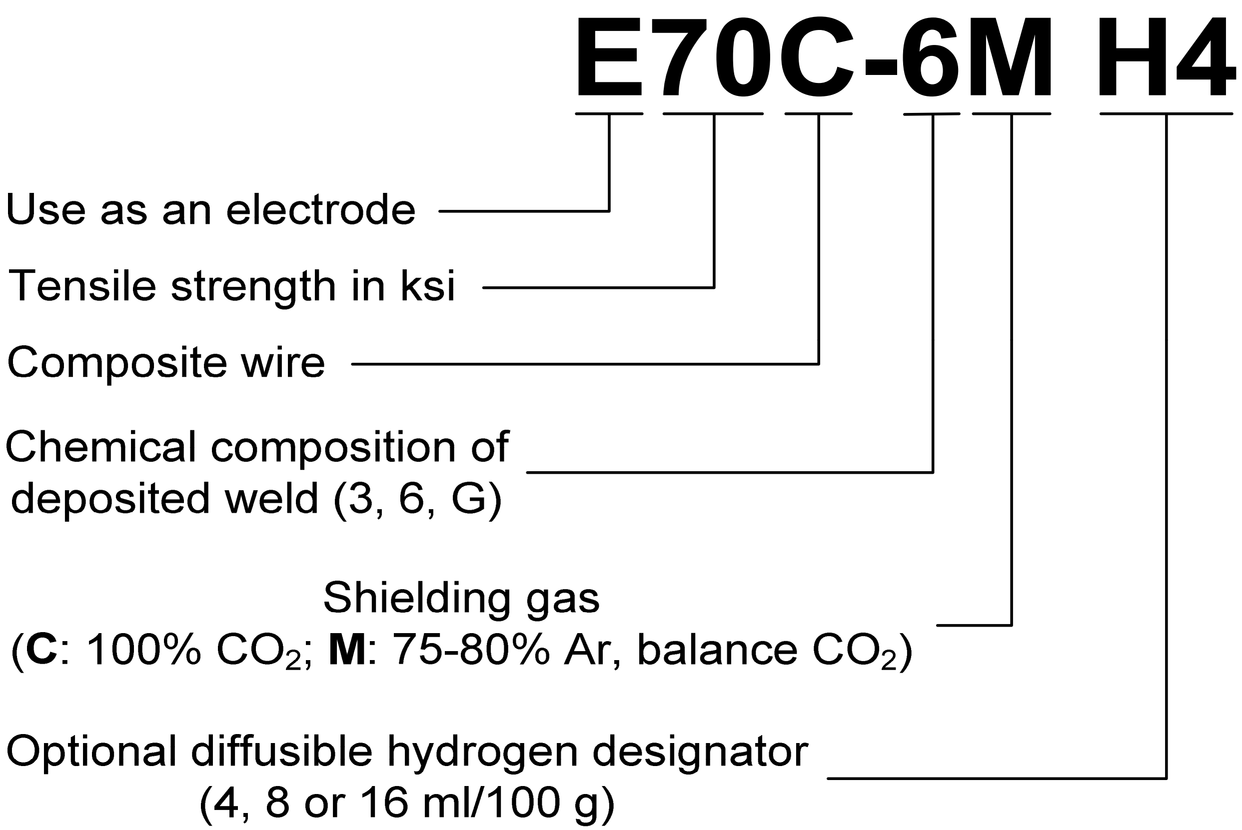
- ER: Use as an electrode or rod
- 70: Tensile strength in ksi
- S: Solid wire
- 3: Chemical composition of electrode (2, 3, 4, 6, 7, G)
- H4: Optional diffusible hydrogen designator (4, 8 or 16 ml/100 g)

Examples

ER70S-6	C-Mn, high Si, 70 ksi min UTS
ER80S-B2	Cr-Mo grade, 80 ksi min UTS
ER100S-2	HSLA grade (Cr, Ni, Mo, Cu), 100 ksi min UTS

AWS Classification for Composite Steel Wires

AWS A5.18



E70C-6M H4

Use as an electrode

Tensile strength in ksi

Composite wire

Chemical composition of deposited weld (3, 6, G)

Shielding gas (**C**: 100% CO_2; **M**: 75-80% Ar, balance CO_2)

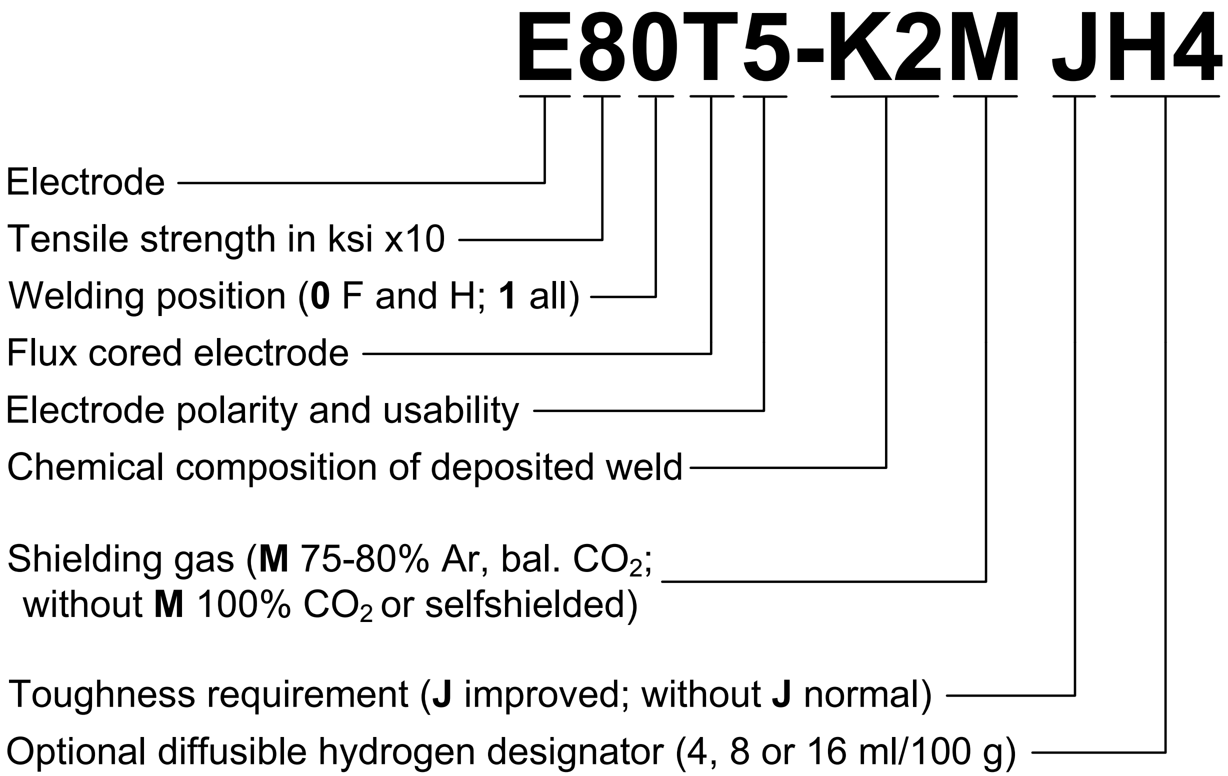
Optional diffusible hydrogen designator (4, 8 or 16 ml/100 g)

Examples

E70C-3C	0.12%C-1.75%Mn-0.9%Si-0.5%Ni-0.2%Cr-0.3%Mo-0.5%Cu, high Si, 70 ksi min UTS, 100% CO_2

FCAW Electrode Classification

AWS A5.29



E80T5-K2M JH4

Electrode

Tensile strength in ksi x10

Welding position (**0** F and H; **1** all)

Flux cored electrode

Electrode polarity and usability

Chemical composition of deposited weld

Shielding gas (**M** 75-80% Ar, bal. CO_2; without **M** 100% CO_2 or selfshielded)

Toughness requirement (**J** improved; without **J** normal)

Optional diffusible hydrogen designator (4, 8 or 16 ml/100 g)

Example

E91T1-D1	90-110 min ksi, all position, CO_2 shielded, DCEP, 1.25/2.00 Mn and 0.25/0.55 Mo

ASME Requirements Preheat, PWHT and Temper Bead Welding

ASME Section III Division 1 – NB – Preheat Requirements

- NB-4610, Welding Preheat Requirements
  - NB-4611, When is Preheat Necessary
    - States preheat temperature is dependent on a number of factors
      - Chemical analysis
      - Degree of restraint
      - Elevated temperature
      - Physical properties
      - Material thickness
    - Provides suggested preheat temperatures depending on the P-Number of the material
    - Refers to non-mandatory Appendix D
      - Preheat temperature is based on chemistry, thickness and/or strength of the material
  - NB-4612, Preheating Methods
  - NB-4613, Interpass Temperature
    - Applicable to quench and tempered materials

ASME B31.1 – Power Piping – Preheat Requirements

- 131, Welding Preheat
  - 131.1, Minimum Preheat Requirements
    - Provides minimum preheat temperatures depending on the material P-No.
    - The preheat temperature should be achieved 3 in. or 1.5 times the material thickness which ever is greater from the weld joint
  - 131.2, Different P-Number Materials
    - The minimum preheat temperature shall be the highest of the two recommended temperatures
  - 131.3, Preheat Temperature Verification
    - Specifies how to monitor the preheat temperature
  - 131.4, Preheat Temperature
    - Should be 50ºF unless otherwise specified depending on material P-No.
    - Identifies the governing thickness as the thicker of the two nominal base materials being welded
  - 131.6, Interruption of Welding
    - Provides requirements for when welding is interrupted and varies depending on material being welded

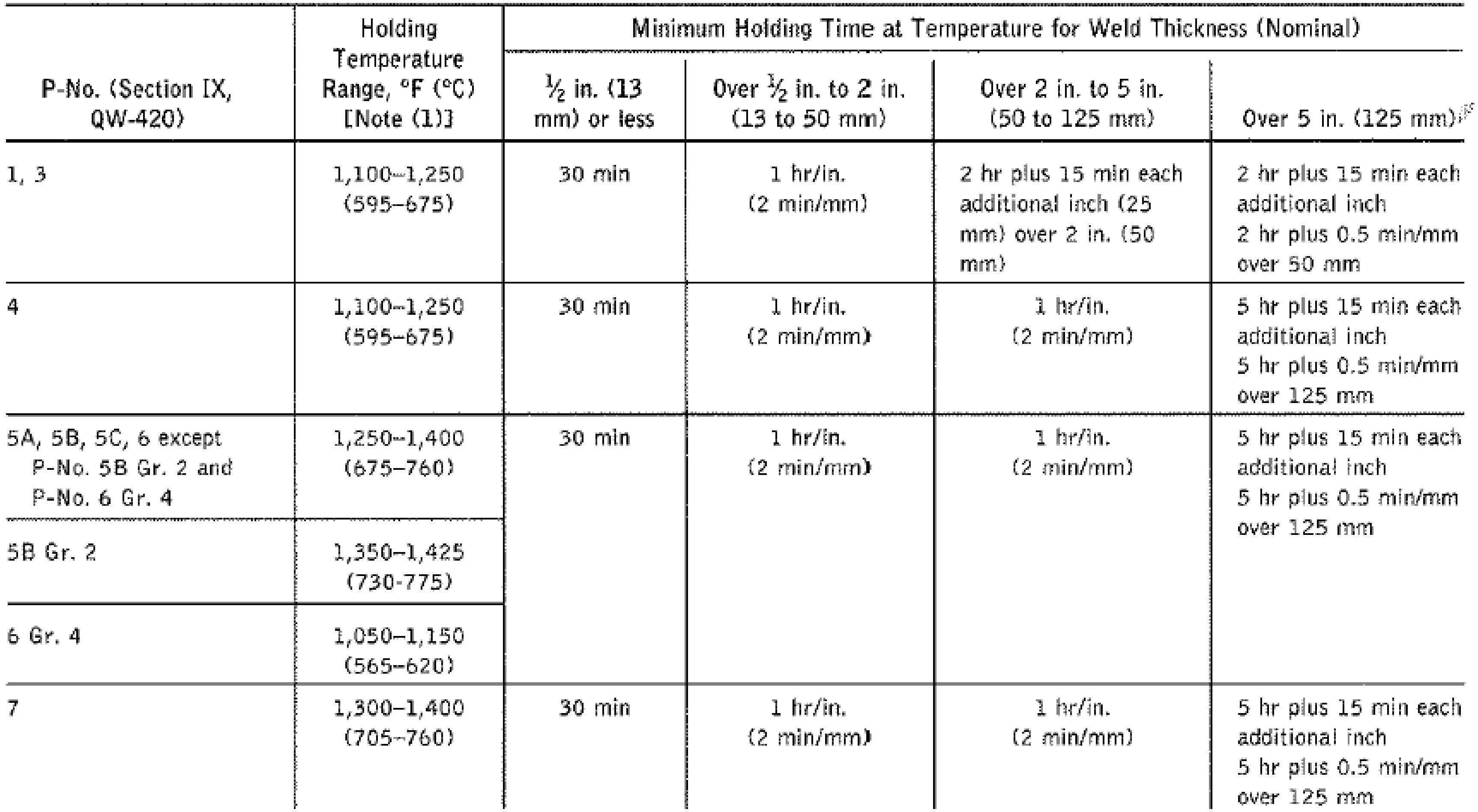
Comparison of ASME Preheat Requirements

Material	Preheat Recommendations	
	ASME Section III - NB	ASME B31.1
P-No. 1 **(Carbon Steel)**	200ºF for ≤ 0.30%C and >1.5” thick	175ºF for > 0.30%C and >1” thick
	250ºF for > 0.30%C and >1” thick	
	50ºF for all other materials	50ºF for all other materials
P-No. 5 **(2.25Cr 1 Mo)**	400ºF for 60 ksi SMTS or specified minimum Cr >6.0% and 01.5” thick	400ºF for 60 ksi SMTS or specified minimum Cr >6.0% and 0.5” thick
	300ºF for all other materials	300ºF for all other materials

ASME Section III Division 1 – NB – PWHT Requirements

- NB-4620, Postweld Heat Treatment
  - NB-4621, Heating and Cooling Methods
    - PWHT may be performed by suitable means provided heating and cooling rates, metal temperature , uniformity and temperature control are maintained
  - NB-4622, PWHT Time and Temperature Requirements
    - NB-4622.1, General PWHT requirements
    - NB-4622.2, Time-Temperature Recordings
    - NB-4622.3, Definition of Nominal Thickness Governing PWHT
    - NB-4622.4, Hold Time at Temperature
      - Does allow for lower temperatures for longer times with addition testing requirements
    - NB-4622.5, Requirements for different P-No.
    - NB-4622.7, Exemptions to Mandatory Requirements

ASME Section III Division 1 – NB – PWHT Requirements



P-No. (Section IX, QW-420)	Holding Temperature Range, °F (°C) [Note (1)]	Minimum Holding Time at Temperature for Weld Thickness (Nominal)			
		½ in. (13 mm) or less	Over ½ in. to 2 in. (13 to 50 mm)	Over 2 in. to 5 in. (50 to 125 mm)	Over 5 in. (125 mm)
1, 3	1,100–1,250 (595–675)	30 min	1 hr/in. (2 min/mm)	2 hr plus 15 min each additional inch (25 mm) over 2 in. (50 mm)	2 hr plus 15 min each additional inch 2 hr plus 0.5 min/mm over 50 mm
4	1,100–1,250 (595–675)	30 min	1 hr/in. (2 min/mm)	1 hr/in. (2 min/mm)	5 hr plus 15 min each additional inch 5 hr plus 0.5 min/mm over 125 mm
5A, 5B, 5C, 6 except P-No. 5B Gr. 2 and P-No. 6 Gr. 4	1,250–1,400 (675–760)	30 min	1 hr/in. (2 min/mm)	1 hr/in. (2 min/mm)	5 hr plus 15 min each additional inch 5 hr plus 0.5 min/mm over 125 mm
5B Gr. 2	1,350–1,425 (730-775)				
6 Gr. 4	1,050–1,150 (565–620)				
7	1,300–1,400 (705–760)	30 min	1 hr/in. (2 min/mm)	1 hr/in. (2 min/mm)	5 hr plus 15 min each additional inch 5 hr plus 0.5 min/mm over 125 mm

ASME Section III Division 1 – NB – PWHT Requirements

- NB-4620, Postweld Heat Treatment
  - NB-4622, PWHT Time and Temperature Requirements
    - NB-4622.4, Hold Time at Temperature
      - Does allow for lower temperatures for longer times with addition testing requirements

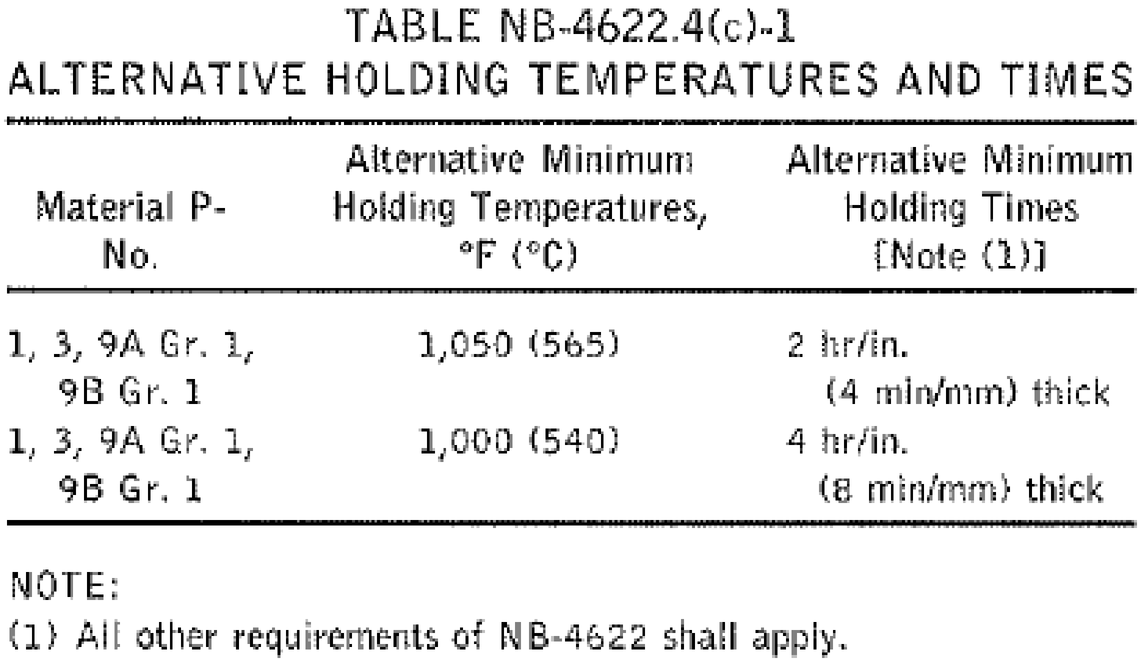


TABLE NB-4622.4(c)-1
ALTERNATIVE HOLDING TEMPERATURES AND TIMES

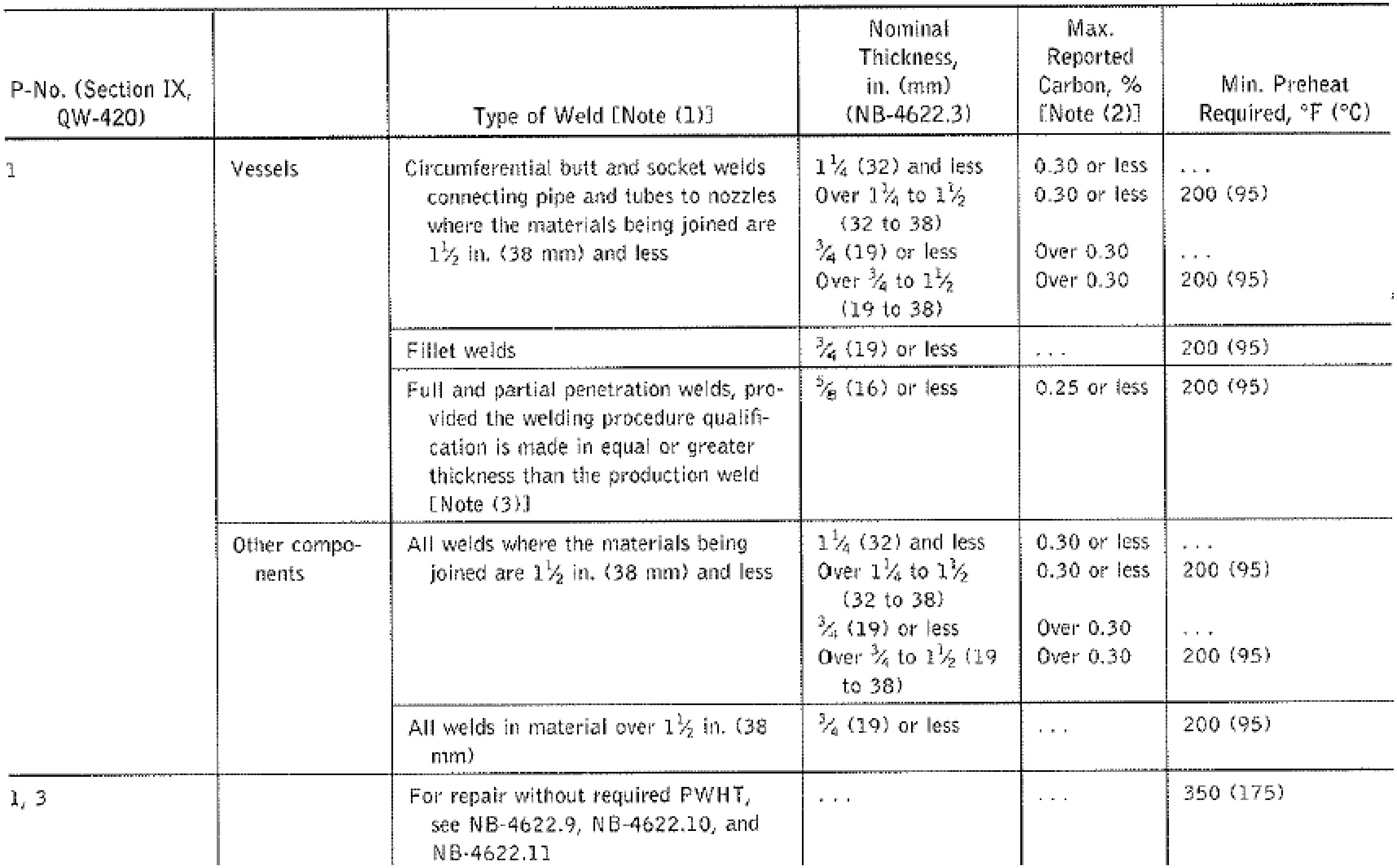
Material P-No.	Alternative Minimum Holding Temperatures, °F (°C)	Alternative Minimum Holding Times [Note (1)]
1, 3, 9A Gr. 1, 9B Gr. 1	1,050 (565)	2 hr/in. (4 min/mm) thick
1, 3, 9A Gr. 1, 9B Gr. 1	1,000 (540)	4 hr/in. (8 min/mm) thick

NOTE:
(1) All other requirements of NB-4622 shall apply.

ASME Section III Division 1 – NB – PWHT Exemptions

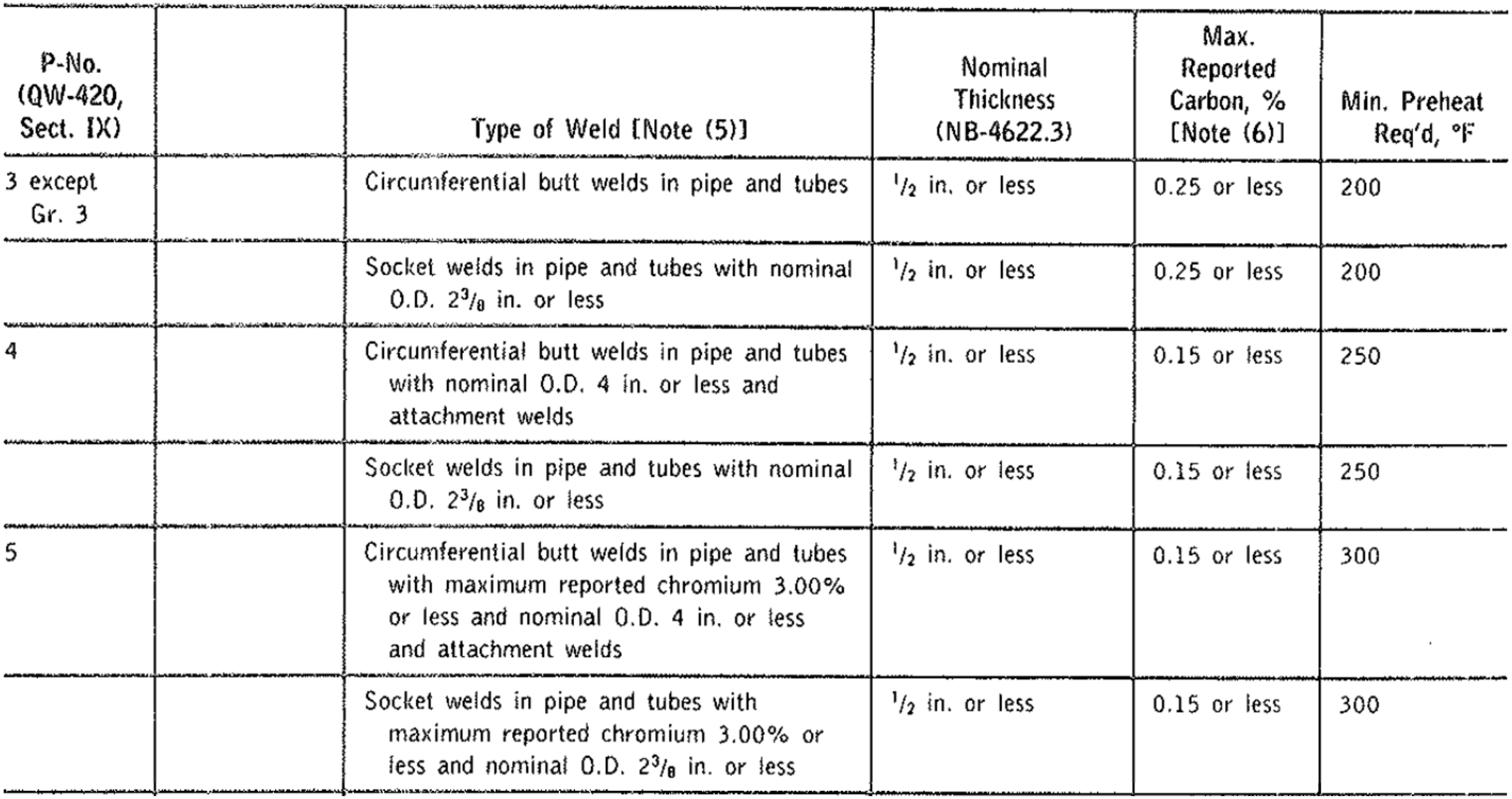
- NB-4620, Postweld Heat Treatment
  - NB-4622, PWHT Time and Temperature Requirements
    - NB-4622.7, Exemptions to Mandatory Requirements
      - Nonferrous material
      - Exempted welds (Table NB-4622.7 (b)-1)
      - Welds subjected to temperatures above the PWHT temperature
      - Welds connecting nozzles to components or branch to pipe in accordance to NB-4622.8 repairs to vessels (i.e., temper bead weld repair)
      - Weld repairs to vessels in accordance to NB-4622.9 (i.e., temper bead weld repair)
      - Weld repairs to cladding after final PWHT in accordance to NB-4622.10
      - Weld repairs to dissimilar metal welds after final PWHT in accordance to NB-4622.11 (i.e., temper bead weld repair)

ASME Section III Division 1 – NB – PWHT Exemptions



P-No. (Section IX, QW-420)		Type of Weld [Note (1)]	Nominal Thickness, in. (mm) (NB-4622.3)	Max. Reported Carbon, % [Note (2)]	Min. Preheat Required, °F (°C)
1	Vessels	Circumferential butt and socket welds connecting pipe and tubes to nozzles where the materials being joined are 1½ in. (38 mm) and less	1¼ (32) and less	0.30 or less	. . .
			Over 1¼ to 1½ (32 to 38)	0.30 or less	200 (95)
			¾ (19) or less	Over 0.30	. . .
			Over ¾ to 1½ (19 to 38)	Over 0.30	200 (95)
		Fillet welds	¾ (19) or less	. . .	200 (95)
		Full and partial penetration welds, provided the welding procedure qualification is made in equal or greater thickness than the production weld [Note (3)]	⅝ (16) or less	0.25 or less	200 (95)
	Other components	All welds where the materials being joined are 1½ in. (38 mm) and less	1¼ (32) and less	0.30 or less	. . .
			Over 1¼ to 1½ (32 to 38)	0.30 or less	200 (95)
			¾ (19) or less	Over 0.30	. . .
			Over ¾ to 1½ (19 to 38)	Over 0.30	200 (95)
		All welds in material over 1½ in. (38 mm)	¾ (19) or less	. . .	200 (95)
1, 3		For repair without required PWHT, see NB-4622.9, NB-4622.10, and NB-4622.11	. . .	. . .	350 (175)

ASME Section III Division 1 – NB – PWHT Exemptions



P-No. (QW-420, Sect. IX)		Type of Weld [Note (5)]	Nominal Thickness (NB-4622.3)	Max. Reported Carbon, % [Note (6)]	Min. Preheat Req'd, °F
3 except Gr. 3		Circumferential butt welds in pipe and tubes	$^1/_2$ in. or less	0.25 or less	200
		Socket welds in pipe and tubes with nominal O.D. $2^3/_8$ in. or less	$^1/_2$ in. or less	0.25 or less	200
4		Circumferential butt welds in pipe and tubes with nominal O.D. 4 in. or less and attachment welds	$^1/_2$ in. or less	0.15 or less	250
		Socket welds in pipe and tubes with nominal O.D. $2^3/_8$ in. or less	$^1/_2$ in. or less	0.15 or less	250
5		Circumferential butt welds in pipe and tubes with maximum reported chromium 3.00% or less and nominal O.D. 4 in. or less and attachment welds	$^1/_2$ in. or less	0.15 or less	300
		Socket welds in pipe and tubes with maximum reported chromium 3.00% or less and nominal O.D. $2^3/_8$ in. or less	$^1/_2$ in. or less	0.15 or less	300

ASME Section III Division 1 – NB – PWHT Requirements

- NB-4620, Postweld Heat Treatment
  - NB-4623, PWHT Heating and Cooling Rates
    - Above 800ºF, the heating and cooling rate shall not exceed 400ºF divided by the maximum material thickness per hour
    - Heating and cooling rates shall be between 400 and 100ºF/hr
    - There shall not be a temperature gradient greater than 250ºF per 15 feet of weld length
  - NB-4624, Methods of PWHT
- NB-4630, PWHT of Welds Other Than Final PWHT
- NB-4650, PWHT after Bending or Forming
- NB-4660, PWHT of Electroslag Welds
  - Electroslag welds in ferritic material over 1.5-in. thick shall be given a grain refining heat treatment

ASME B31.1 – Power Piping – PWHT Requirements

- 132, Postweld Heat Treatment
  - 132.1, Minimum PWHT Requirements
    - Refers to Table 132
    - Allows for lower temperature and longer time
  - 132.2, Mandatory PWHT Requirements
    - PWHT may be performed by suitable means provided heating and cooling rates, metal temperature, uniformity and temperature control are maintained
    - Refers to Table 132 for time and temperature

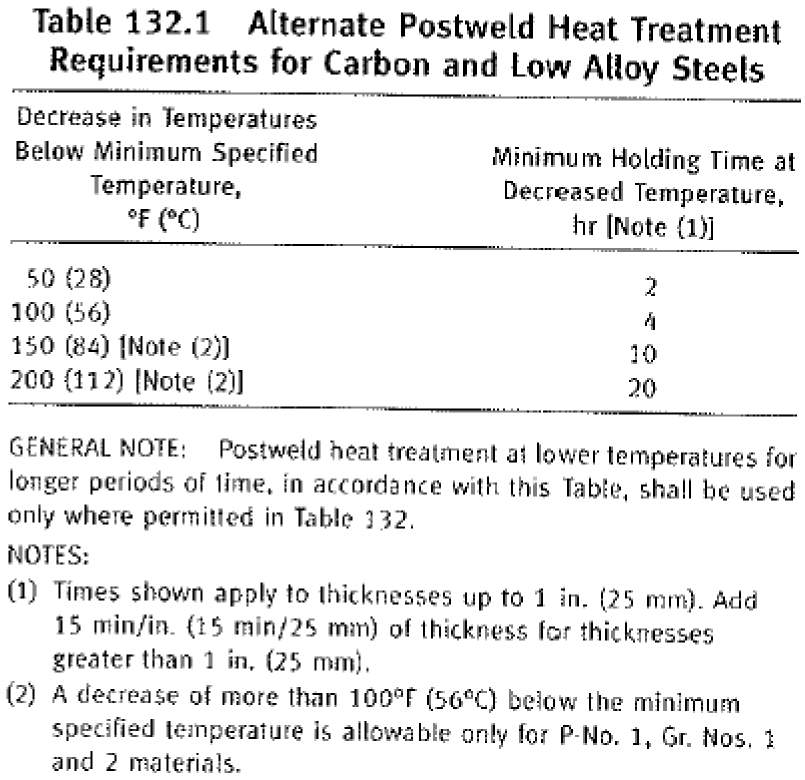


Table 132.1 Alternate Postweld Heat Treatment Requirements for Carbon and Low Alloy Steels

Decrease in Temperatures Below Minimum Specified Temperature, °F (°C)	Minimum Holding Time at Decreased Temperature, hr [Note (1)]
50 (28)	2
100 (56)	4
150 (84) [Note (2)]	10
200 (112) [Note (2)]	20

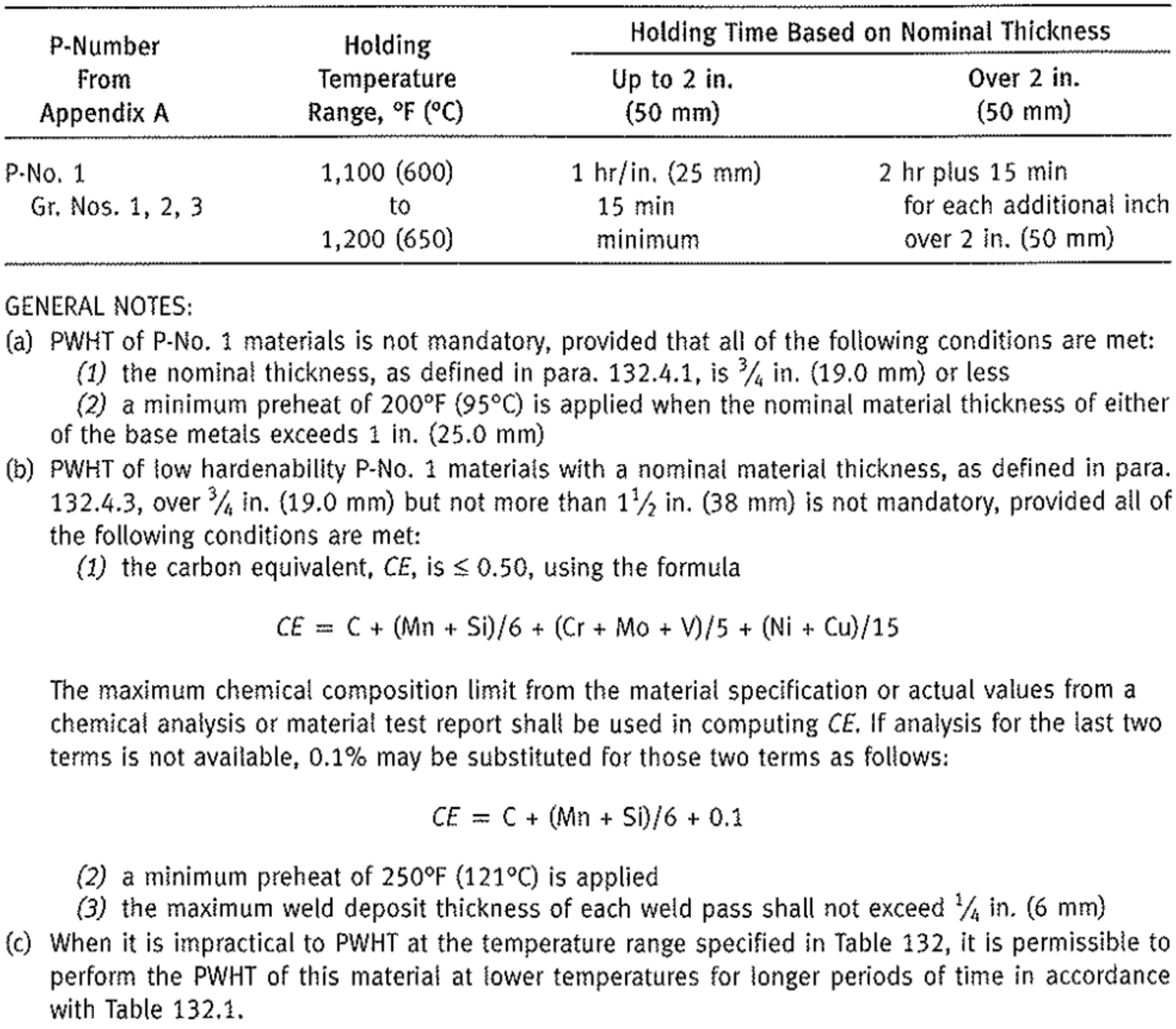
GENERAL NOTE: Postweld heat treatment at lower temperatures for longer periods of time, in accordance with this Table, shall be used only where permitted in Table 132.

NOTES:

(1) Times shown apply to thicknesses up to 1 in. (25 mm). Add 15 min/in. (15 min/25 mm) of thickness for thicknesses greater than 1 in. (25 mm).

(2) A decrease of more than 100°F (56°C) below the minimum specified temperature is allowable only for P-No. 1, Gr. Nos. 1 and 2 materials.

ASME B31.1 – Power Piping – PWHT Requirements



P-Number From Appendix A	Holding Temperature Range, °F (°C)	Holding Time Based on Nominal Thickness	
		Up to 2 in. (50 mm)	Over 2 in. (50 mm)
P-No. 1 Gr. Nos. 1, 2, 3	1,100 (600) to 1,200 (650)	1 hr/in. (25 mm) 15 min minimum	2 hr plus 15 min for each additional inch over 2 in. (50 mm)

GENERAL NOTES:

(a) PWHT of P-No. 1 materials is not mandatory, provided that all of the following conditions are met:
  - *(1)* the nominal thickness, as defined in para. 132.4.1, is $^3/_4$ in. (19.0 mm) or less
  - *(2)* a minimum preheat of 200°F (95°C) is applied when the nominal material thickness of either of the base metals exceeds 1 in. (25.0 mm)

(b) PWHT of low hardenability P-No. 1 materials with a nominal material thickness, as defined in para. 132.4.3, over $^3/_4$ in. (19.0 mm) but not more than $1^1/_2$ in. (38 mm) is not mandatory, provided all of the following conditions are met:
  - *(1)* the carbon equivalent, *CE*, is ≤ 0.50, using the formula

$$CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$$

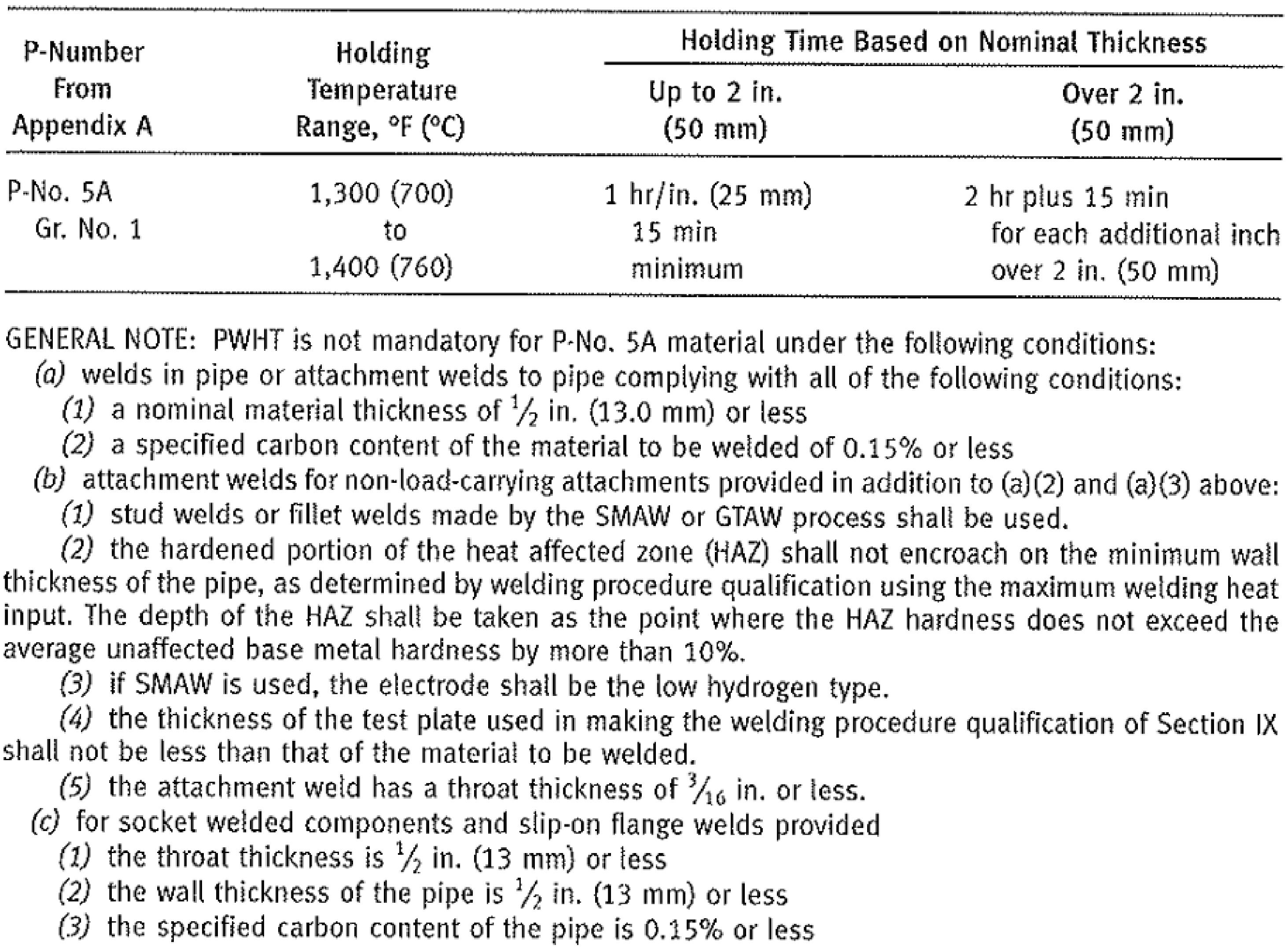
The maximum chemical composition limit from the material specification or actual values from a chemical analysis or material test report shall be used in computing *CE*. If analysis for the last two terms is not available, 0.1% may be substituted for those two terms as follows:

$$CE = C + (Mn + Si)/6 + 0.1$$

  - *(2)* a minimum preheat of 250°F (121°C) is applied
  - *(3)* the maximum weld deposit thickness of each weld pass shall not exceed $^1/_4$ in. (6 mm)

(c) When it is impractical to PWHT at the temperature range specified in Table 132, it is permissible to perform the PWHT of this material at lower temperatures for longer periods of time in accordance with Table 132.1.

ASME B31.1 – Power Piping – PWHT Requirements



P-Number From Appendix A	Holding Temperature Range, °F (°C)	Holding Time Based on Nominal Thickness	
		Up to 2 in. (50 mm)	Over 2 in. (50 mm)
P-No. 5A Gr. No. 1	1,300 (700) to 1,400 (760)	1 hr/in. (25 mm) 15 min minimum	2 hr plus 15 min for each additional inch over 2 in. (50 mm)

GENERAL NOTE: PWHT is not mandatory for P-No. 5A material under the following conditions:
- *(a)* welds in pipe or attachment welds to pipe complying with all of the following conditions:
  - *(1)* a nominal material thickness of ½ in. (13.0 mm) or less
  - *(2)* a specified carbon content of the material to be welded of 0.15% or less
- *(b)* attachment welds for non-load-carrying attachments provided in addition to (a)(2) and (a)(3) above:
  - *(1)* stud welds or fillet welds made by the SMAW or GTAW process shall be used.
  - *(2)* the hardened portion of the heat affected zone (HAZ) shall not encroach on the minimum wall thickness of the pipe, as determined by welding procedure qualification using the maximum welding heat input. The depth of the HAZ shall be taken as the point where the HAZ hardness does not exceed the average unaffected base metal hardness by more than 10%.
  - *(3)* if SMAW is used, the electrode shall be the low hydrogen type.
  - *(4)* the thickness of the test plate used in making the welding procedure qualification of Section IX shall not be less than that of the material to be welded.
  - *(5)* the attachment weld has a throat thickness of $^{3}/_{16}$ in. or less.
- *(c)* for socket welded components and slip-on flange welds provided
  - *(1)* the throat thickness is ½ in. (13 mm) or less
  - *(2)* the wall thickness of the pipe is ½ in. (13 mm) or less
  - *(3)* the specified carbon content of the pipe is 0.15% or less

ASME B31.1 – Power Piping – PWHT Requirements

- 132, Postweld Heat Treatment
  - 132.3 Exemptions to Mandatory PWHT Requirements
    - Welds in nonferrous materials
    - Welds exempted in Table 132
    - Welds subject to temperatures above the lower critical temperature provided proper qualification
    - Exemptions are based on the actual chemistry of the material
  - 132.4 Definition of Thickness Governing PWHT
    - Table 132 uses weld thickness (i.e., “nominal thickness”) to determine time and temperature but use material thickness (i.e., “nominal material thickness”) for exemptions
  - 132.5 PWHT Heating and Cooling Rates
    - Above 600ºF, the heating and cooling rate shall not exceed 600ºF per hour divided by the ½ the maximum material thickness
    - Heating and cooling rates shall not exceed 600ºF/hr
      - More specifics depending on material
  - 132.6 and 132.7 describe furnace heating and local heating requirements

Comparison of ASME PWHT Requirements

ASME Code	P-No.	Hold Temperature	Material Thickness			
			Up to 0.5 in.	0.5 in. – 2 in.	> 2 in. – 5 in.	Over 5 in.
Sec. III – NB	1	1100 ºF – 1250 ºF	30 min.	1 hr/in.	2 hr plus 15 min. each additional in.	5 hr. plus 15 min. each additional in.
	5A	1250 ºF – 1400 ºF	30 min.	1 hr/in.	1 hr/in.	5 hr. plus 15 min. each additional in.
B31.1	1	1100 ºF – 1200 ºF	1 hr/in. (15 min. minimum)		2 hr. plus 15 min. each additional in.	
	5A	1300 ºF – 1400 ºF	1 hr/in. (15 min. minimum)		2 hr. plus 15 min. each additional in.	

ASME Section IX – Preheat and PWHT Procedure Variables

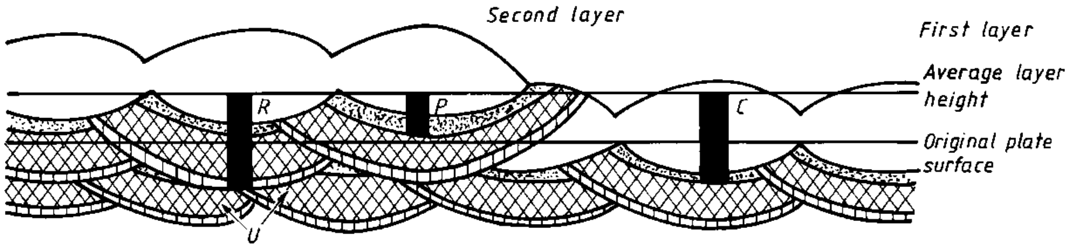
Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-406 Preheat	.1	Decrease > 100ºF	X		
	.2	φ Preheat Maintenance			X
	.3	Increase > 100ºF (IP)		X	
	.7	φ > 10% Amperage, Number of Cycles, etc	X		
QW-407 PWHT	.1	φ PWHT	X		
	.2	φ PWHT (T & T Range)		X	
	.4	T Limits	X		
	.8	φ PWHT, PWHT Cycles, or Separate PWHT Time or Temperature	X		

Typical ASME Section IX Requirements

- For SMAW process
  - Preheat variables
    - Decrease by more than 100ºF requires requalification
  - Interpass variables
    - Increase by more than 100ºF requires requalification if toughness is a requirement
  - PWHT variables
    - Change in PWHT temperature schedules requires requalification
      - PWHT above upper transformation temperature, PWHT below lower transformation temperature, etc.
    - Change in PWHT time and temperature ranges requires requalification if toughness is a requirement
    - For specific ferrous materials (e.g., P-No. 7, 8 and 49), a change in material thickness greater than 1.1X the thickness of the material qualified requires requalification

Temper Bead Welding – Background

- Temper bead welding uses the heat from welding of subsequent beads to temper HAZ of previous deposited passes
  - Tempering reduces HAZ hardness
- Temper bead welding is most commonly used for repair applications as an alternative to repairs using PWHT
  - Temper bead welding is essentially a local PWHT



Two-layer refinement criterion: Max. fusion boundary/ depth, second layer (P) < max. fusion boundary depth, first layer + average layer height, first layer (C) < max. depth of refining zone, second layer (R)

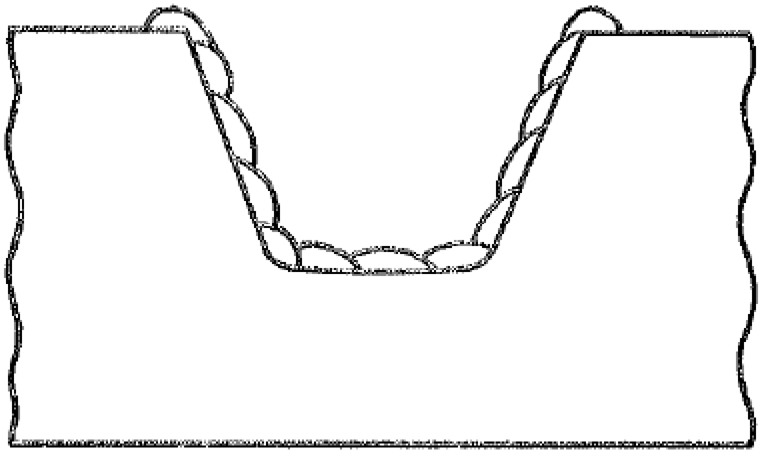
Note:

1. Single weld bead zones
2. All measurements with respect to the original surface
3. The fusion boundary is used as a first order approximation for the depth of the coarse-grained HAZ

ASME Section III Division 1 – NB – Temper Bead Welding

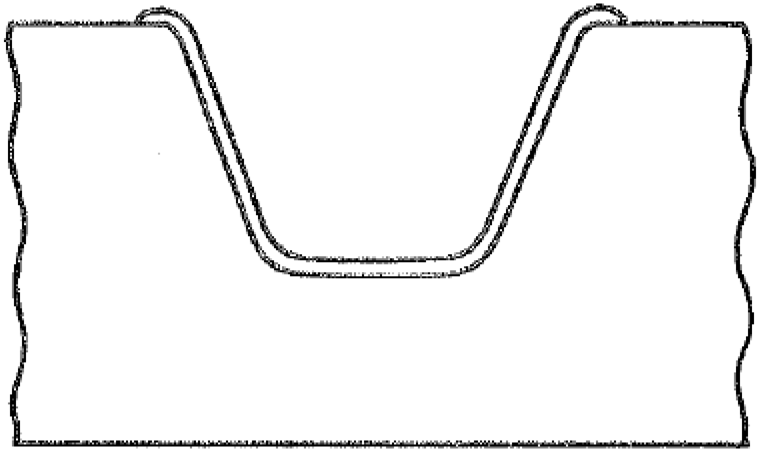
- NB-4622.9, Temper Bead Weld Repair
  - Limited to P-No. 1 (C. Steel) and P-No.3 (0.5 Mo Steel) materials using A-No. 1, 2, 10 and 11 filler metals
  - Repair shall be no more than 100 in.^{2} in area and no greater than 1/3 material thickness
  - Qualified in accordance with ASME IX with additional requirements
    - Use SMAW welding with low-hydrogen electrodes and low-hydrogen welding practice
    - Preheat temperature shall be a minimum of 350ºF
    - Interpass temperature shall be a maximum of 450ºF
    - The weld are shall be maintained at a temperature of 450 – 550ºF after welding for 2 hours for P-No. 1 materials and 4 hours for P-No. 3 materials
    - Specific weld bead locations specified and electrode diameter specified per layer
  - Inspection requirements prior to welding, during welding and after the welding is complete

ASME Section III Division 1 – NB – Temper Bead Welding



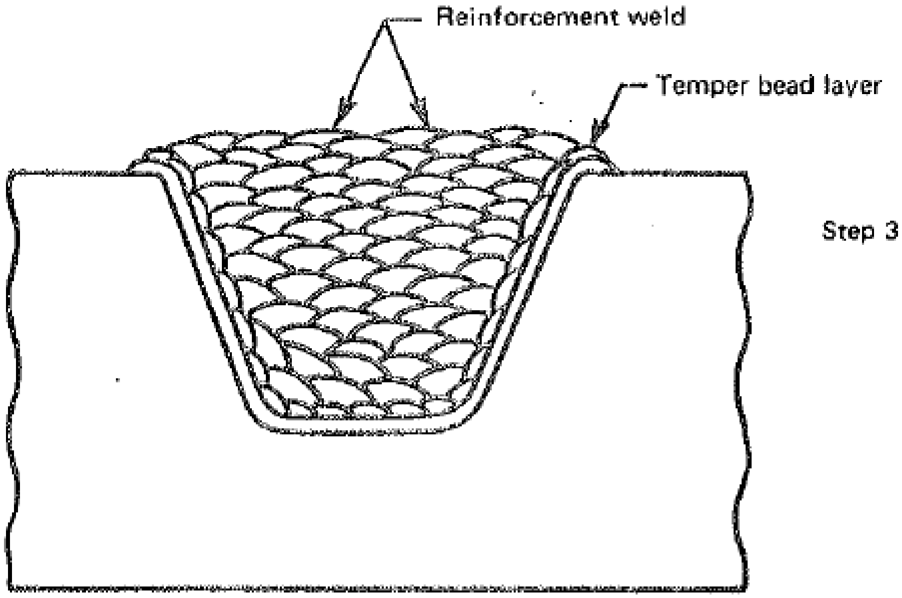
Step 1: Butter cavity with one layer of weld metal using 3/32 in. diameter coated electrode.

ASME Section III Division 1 – NB – Temper Bead Welding



Step 2: Remove the weld bead crown of the first layer of grinding.

ASME Section III Division 1 – NB – Temper Bead Welding

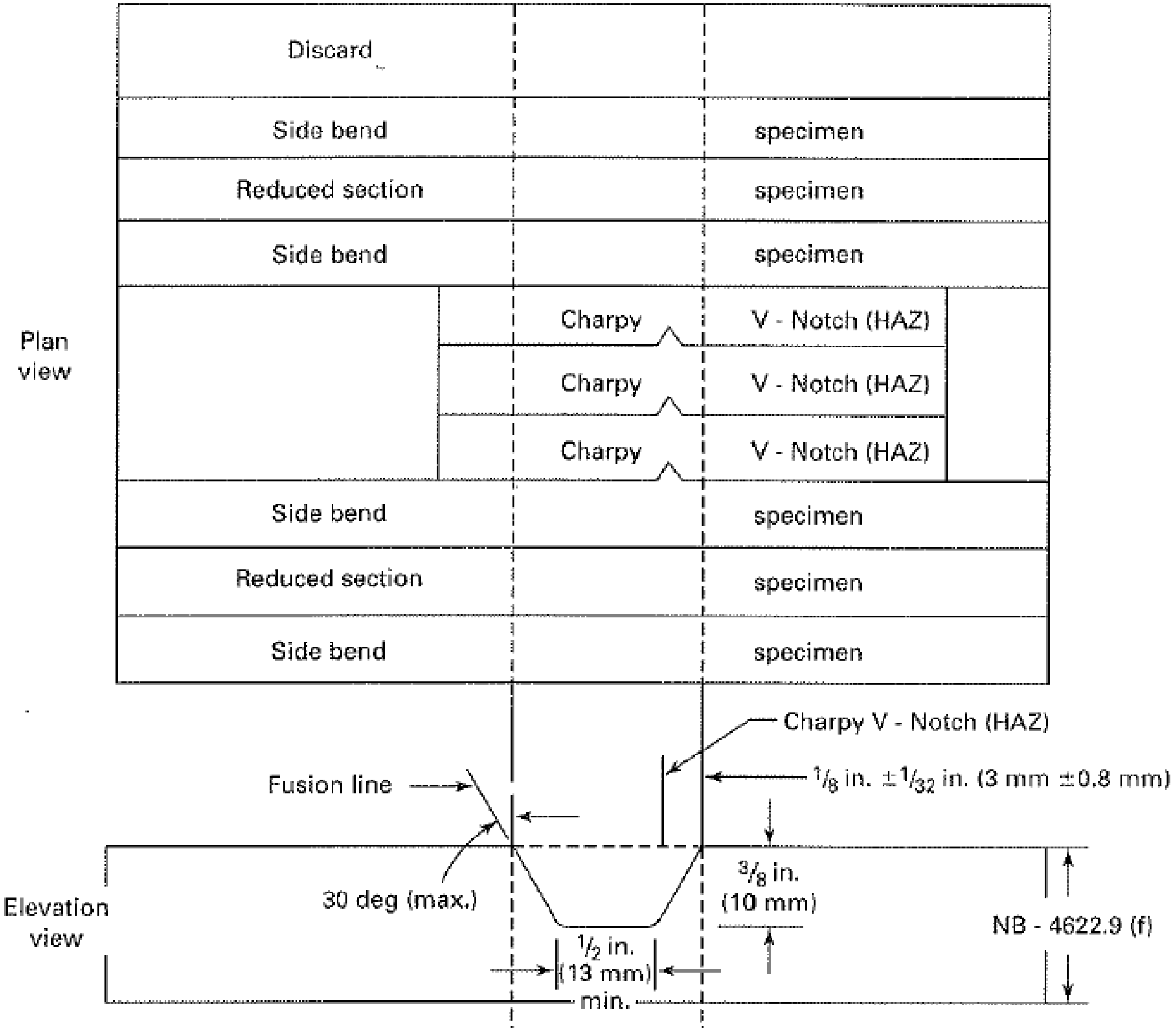


Step 3: The second layer shall be deposited with a 1/8 in. diameter electrode. Subsequent layers shall be deposited with welding electrodes no larger than 5/32 in. maximum diameter. Bead deposition shall be performed in a manner as shown. Particular care shall be taken in the application of the temper bead reinforcement weld at the tie-in points as well as its removal to ensure that the heat affected zone of the base metal and the deposited weld metal is tempered and the resulting surface is substantially flush.

ASME Section III Division 1 – NB – Temper Bead Welding

- NB-4622.9(f), Welding Procedure Qualification Test Plate
  - Qualification plate shall be the same P-No as the material in the field including same PWHT conditions
  - Depth of cavity shall be at least half the depth of the actual repair but not less than 1 in.
  - Test plate assembly shall be at least twice the depth of the cavity
  - The test assembly around the groove shall be at least the thickness of the test assembly but not less than 6 in.

ASME Section III Division 1 – NB – Temper Bead Welding



ASME Section IX – Temper Bead Welding Requirements

- Temper bead weld procedure qualification is more restrictive than typical welding procedures
    - Additional variables need to be addressed in addition to the weld process variables
- QW-290, Temper Bead Welding
    - QW-290.1, Basic Qualification and Upgrading Existing WPS
    - QW-290.2, Welding Process Restrictions
        - SMAW, GTAW, SAW, GMAW (including FCAW) and PAW is permitted
    - QW-290.3, Variables for Temper Bead Welding Qualification
    - QW-290.5, Test Coupon Preparation and Testing
        - Includes hardness testing requirements
        - Refers to the code of construction for additional testing

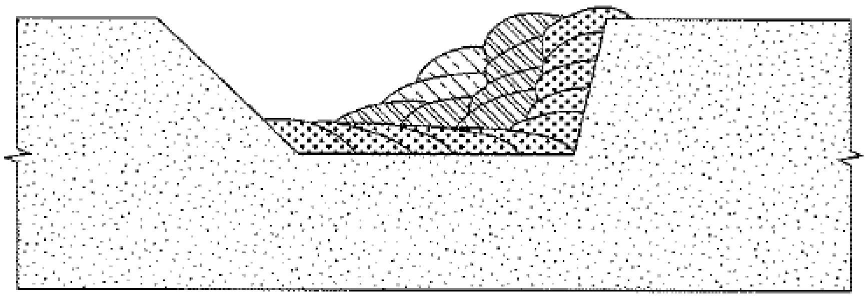
ASME Section IX – Preheat and PWHT Procedure Variables

Paragraph		Brief of Variables	Hardness Essential	Impact Test Essential	Nonessential
QW-402 Joints	.23	+ Fluid Backing	X		
	.24	+ Fluid Backing		X	
QW-403 Base Materials	.25	φ P-No. or Group No.		X	
	.26	> Carbon Equivalent	X		
	.27	> T	X		
QW-404 Filler Metals	.51	Storage			X
	.52	Diffusible Hydrogen			X
QW-406 Preheat	.8	> Interpass Temperature		X	
	.9	< Preheat Maintenance	X		
	.10	Preheat Soak Time			X
	.11	Postweld Bake Out			X

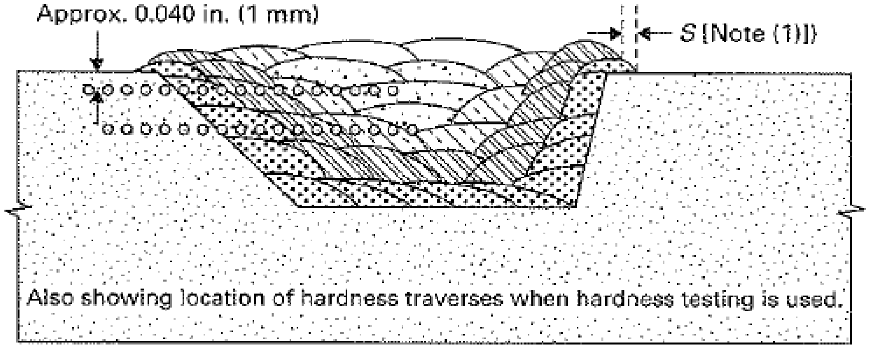
ASME Section IX – Preheat and PWHT Procedure Variables

Paragraph		Brief of Variables	Hardness Essential	Impact Test Essential	Nonessential
QW-408 Gas	.24	Gas Moisture			X
QW-409 Gas	.29	φ Heat Input Ratio	X	X	
QW-410 Technique	.10	φ Single to Multiply Electrodes	X	X	
	.58	- Surface Temper Bead	X	X	
	.59	Φ Type of Welding	X	X	
	.60	+ Thermal Preparation	X	X	
	.61	Surface Bead Placement	X	X	
	.62	Surface Bead Removal Method			X
	.63	Bead Overlap	X	X	
	.65	± Grinding	X	X	

ASME Section IX – Temper Bead Welding



Partially Completed Partial-Penetration Weld

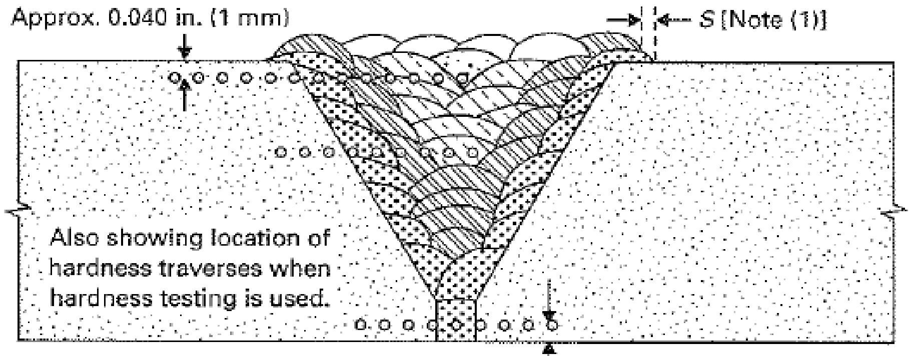


Completed Partial-Penetration Weld

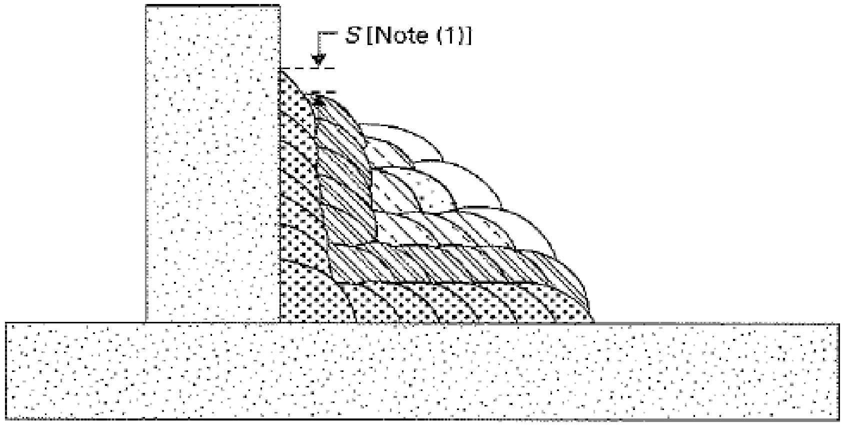
LEGEND
See Note (2)

- ▩ Weld Beads against Base Metal
- ▧ First Layer Tempering Beads
- ▨ Second Layer Tempering Beads
- ⬚ Fill Weld Beads
- ☐ Surface Temper Weld Reinforcing Beads

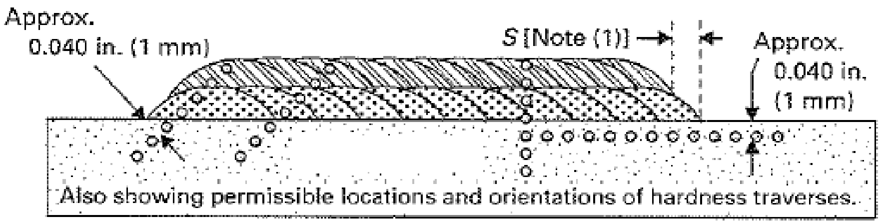
ASME Section IX – Temper Bead Welding



Typical Groove Weld



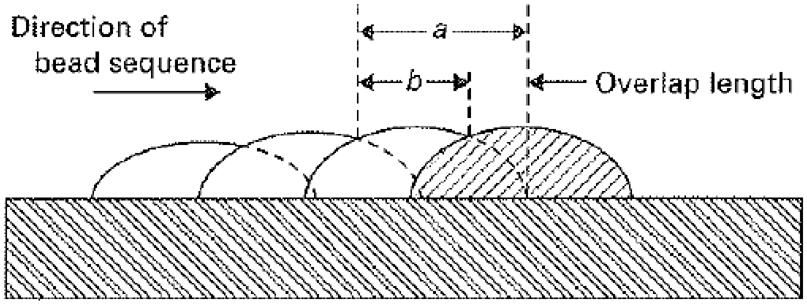
Typical Fillet Weld



Overlay Weld

ASME Section IX – Temper Bead Welding

QW-462.13 MEASUREMENT OF TEMPER BEAD OVERLAP



GENERAL NOTE: Measurement of bead overlap – % overlap length = (a–b)/a × 100%. In this figure, the shaded bead overlaps previous bead by 30% to 40%. The distance *a* is measured before the next bead is deposited.