17BEAE306 ENGINEERING MATERIALS AND METALLURGY 3 0 0 3 100

INTENDED OUTCOMES:

- To impart knowledge on the structure, properties, treatment, testing and applications of metals and on non-metallic materials so as to identity and select suitable materials for various engineering applications.

Review (Not for Exam):
Crystal structure – BCC, FCC and HCP structure – unit cell – crystallographic planes and directions, miller indices – crystal imperfections, point, line, planar and volume defects – Grain size, ASTM grain size number.

UNIT I CONSITITUION OF ALLOYS AND PHASE DIAGRAMS

Constitution of alloys – Solid solutions, substitutional and interstitial – phase diagrams, Isomorphous, eutectic, peritectic, eutectoid and peritectroid reactions, Iron – Iron carbon equilibrium diagram. Classification of steel and cast Iron microstructure, properties and application.

UNIT II FERROUS AND NON FERROUS METALS

Effect of alloying additions on steel (Mn, Si, Cr, Mo, V Ti & W) - stainless and tool steels – HSLA - maraging steels – Gray, White malleable, spheroidal -Graphite - alloy castirons.
Copper and Copper alloys – Brass, Bronze and Cupronickel – Aluminium and Al-Cu – precipitation strengthening treatment – Bearing alloys.

UNIT III MECHANICAL PROPERTIES AND TESTING

Mechanism of plastic deformation, slip and twinning – Types of fracture – Testing of materials under tension, compression and shear loads – Hardness tests (Brinell, Vickers and Rockwell) Impact test Izod and charpy, fatigue and creeptest.

UNIT IV HEAT TREATMENT

Definition – Full annealing, stress relief, recrystallisation and spheroidizing – normalising, hardening and Tempering of steel. Isothermal transformation diagrams – cooling curves superimposed on I.T. diagram CCR - Hardenability, Jominy end quench test – Austempering, martempering – case hardening, carburising, nitriding, cyaniding, carbonitriding – Flame and Induction hardening.

UNIT V INTRODUCTION TO COMPOSITES

Fundamentals of composites - need for composites – Enhancement of properties - classification of composites – Matrix-Polymer matrix composites (PMC), Metal matrix composites (MMC), Ceramic matrix composites (CMC) – Reinforcement – Particle reinforced composites, Fibre reinforced composites. Applications of various types of composites in Automobiles

TEXT BOOKS

SL.NO.	AUTHOR(S)	TITLE OF THE BOOK	PUBLISHER	YEAR OF PUBLICATION
1.	Kenneth G.Budinski and Michael K.Budinski	Engineering Materials",4th Indian Reprint	Prentice-Hall of India Private Limited.	2014
2.	Raghavan.V	Materials Science and Engineering	Prentice Hall of India Pvt. Ltd	1999

REFERENCES

SL.NO.	AUTHOR(S)	TITLE OF THE BOOK	PUBLISHER	YEAR OF PUBLICATION
1.	William D.Callister Jr	Materials Science and Engineering an Introduction", Sixth edition	John Wiley and Sons Inc, New York	2004
2.	Sydney H.Avner	Introduction to Physical Metallurgy	Tata McGraw-Hill Publishing Co. Ltd, New Delhi.	2008

WEBREFERENCE

www.nptel.iitm.ac.in

KARPAGAM ACADEMY OF HIGHER EDUCATION
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COIMBATORE 641 021.
FACULTY OF ENGINEERING
DEPARTMENT OF AUTOMOBILE ENGINEERING
B.E. – AUTOMOBILE ENGINEERING (FULL TIME)
COURSE PLAN

Subject : ENGINEERING MATERIALS AND METALLURGY
Class : III SEMESTER (Automobile)
Sub. Code : 17BEAE306
Branch : AUTOMOBILE ENGINEERING
Faculty : **Dr.R.Sivaprakasam**

FUNDAMENTALS -02 Hours			
Sl. No.	**Topics to be Covered**	**Lecture Duration**	**Support Materials**
1	Crystal structure – BCC, FCC and HCP Structure	1Hour	T2, R3
2	Crystal imperfections -Grain size, ASTM grain size number.	1Hour	T2, R3

UNIT I CONSTITUTION OF ALLOYS & PHASE DIAGRAMS - 10 Hours			
SI.No	**Topics to be Covered**	**Lecture Duration**	**Support Materials**
1.	Constitution of alloys	1Hour	T1,R1,R3
2.	Solid solutions - Substitutional and Interstitial	1 Hour	
3.	Phase Diagrams - Isomorphous, eutectic, peritectic	2 Hour	
4.	Phase Diagirams - Eutectoid and peritectroid reactions	1 Hour	
5.	Iron – Iron Carbide Equilibrium Diagram.	2 Hour	
6.	Classification of Steel and Cast Iron microstructure	1 Hour	
7.	Properties and applications of Steel and Cast Iron	1 Hour	
8.	*Tutorials*: Objective Questions	1 Hour	

UNIT II FERROUS AND NON FERROUS METALS - 10 Hours			
SI.No ..	**Topics to be Covered**	**Lecture Duration**	**Support Materials**
1.	Effect of alloying additions on steel (Mn, Si, Cr, Mo, V Ti & W)	1 Hour	T2,R2, R3
2.	Stainless Steels and Tool steels	1 Hour	
3.	HSLA and maraging steels	1 Hour	
4.	Gray, White malleable, Spheroidal	1 Hour	
5.	Graphite - Cast iron Alloys	1 Hour	
6.	Copper and Copper alloys	1 Hour	
7.	Brass, Bronze and Cupronickel	1 Hour	
8.	Aluminium and Al-Cu	1 Hour	
9.	Precipitation strengthening treatment & Bearing alloys	1 Hour	
10.	*Tutorials*: Objective Questions	1 Hour	

UNIT III MECHANICAL PROPERTIES AND TESTING – 10 Hours

SI.No.	Topics to be Covered	Lecture Duration	Support Materials
1.	Mechanism of plastic deformation	1 Hour	T1, T2,R2, R3
2.	Slip and Twinning	1 Hour	
3.	Types of Fracture	2 Hour	
4.	Testing of materials under tension	1 Hour	
5.	Testing of materials under compression	1 Hour	
6.	Testing of materials under shear loads	1 Hour	
7.	Hardness tests (Brinell, Vickers and Rockwell)	1 Hour	
8.	Impact test Izod and charpy, fatigue and creeptest	1 Hour	
9.	Tutorial: Objective Questions Review	1 Hour	

UNIT IV HEAT TREATMENT – 10 Hours

SI.No.	Topics to be Covered	Lecture Duration	Support Materials
1.	Definition – Full annealing, stress relief	1 Hour	T1, T2,R2, R3
2.	Recrystallisation and spheroidizing	1 Hour	
3.	Normalising, hardening and Tempering of steel	1 Hour	
4.	Isothermal transformation diagrams	1 Hour	
5.	Cooling curves superimposed on T.T. Diagram	1 Hour	
6.	Hardenability, Jominy end quench test	1 Hour	
7.	Austempering, martempering	1 Hour	
8.	Case hardening, carburising, nitriding, cyaniding, carbonitriding	1 Hour	
9.	Flame and Induction hardening	1 Hour	
10.	*Tutorials*: Objective Questions Review	1 Hour	

UNIT V INTRODUCTION TO COMPOSITES - 11 Hours

SI.No	Topics to be Covered	Lecture Duration	Support Materials
1.	Fundamentals of composites	1 Hour	T1, T2,R2, R3
2.	Need for composites	1 Hour	
3.	Enhancement of properties - classification of composites	1 Hour	
4.	Matrix-Polymer matrix composites (PMC), Metal matrix composites (MMC),	2 Hour	
5.	Ceramic matrix composites (CMC)	1 Hour	
6.	Reinforcement -Particle reinforced composites	1 Hour	
7.	Fibre reinforced composites and Applications of all composites	1 Hour	
8.	Applications of various types of composites.	1 Hour	
9.	*Tutorials*: Metal matrix composites (MMC)	1 Hour	
10.	End Semester Model Question Papers Review	1 Hour	

HOUR ALLOCATION DETAILS

Basics - 02 Hours
Lectures - 45 Hours
Tutorials - 06 Hours

Total hour - 53 Hours

TEXT BOOKS

SL.NO.	AUTHOR(S)	TITLE OF THE BOOK	PUBLISHER	YEAR OF PUBLICATION
1.	Kenneth G.Budinski and Michael K.Budinski	Engineering Materials:Properties and Selection	Prentice-Hall of India Private Limited.	2014
2.	Raghavan.V	Materials Science and Engineering	Prentice Hall of India.	2013

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1.	William D.Callister and David G.Rethwisch	Materials Science and Engineering: An Introduction	John Wiley and Sons Inc, New York	2010
2.	Sydney H.Avner	Introduction to Physical Metallurgy	Tata McGraw- Hill Publishing Co. Ltd, New Delhi.	2008
3				

WEB REFERENCES

1. www.keytometals.com/
2. www.matweb.com
3. http://www.nptel.ac.in

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CONSITITUION OF ALLOYS AND PHASE DIAGRAMS

PHASE DIAGRAMS

- Introduction
- Solubility Limits
- Phases
- Phase Equilibrium
- Interpretation of Phase Diagrams
- Binary Isomorphous Systems (Cu-Ni)
- Development of Microstructure
- Mechanical Properties
- Binary Eutectic Systems
- Development of Eutectic Alloy Microstructure

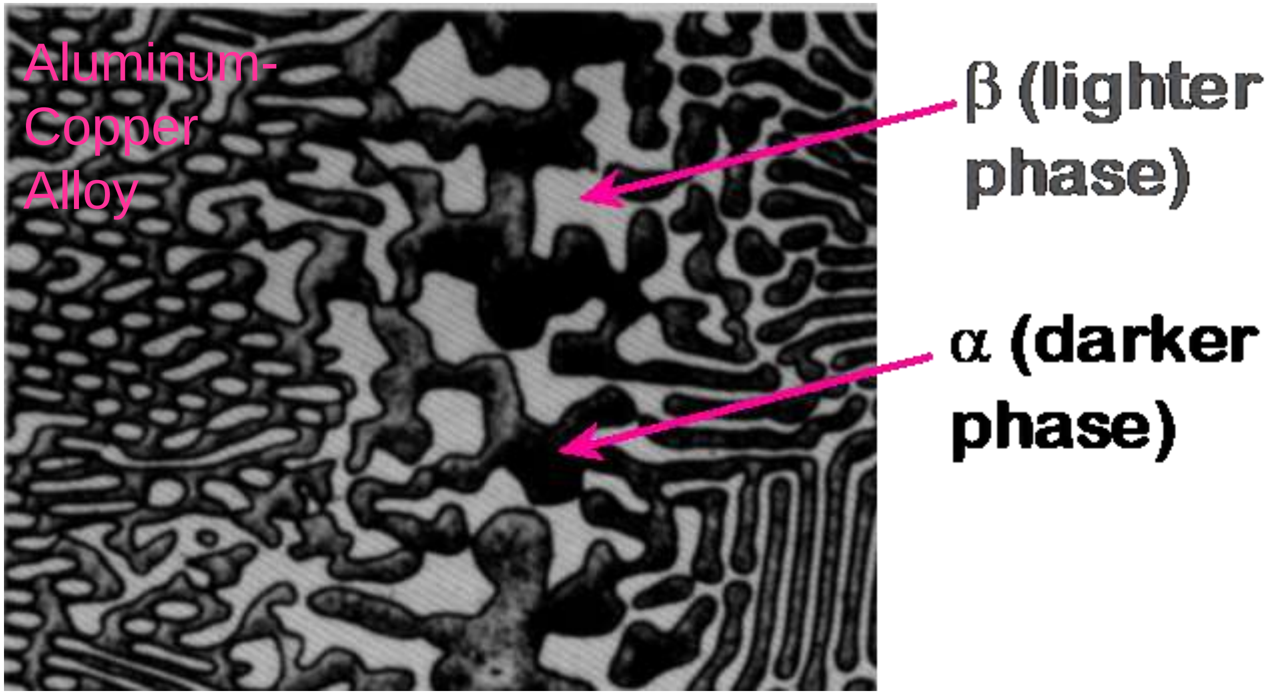
Components and Phases

- Components:

  The elements or compounds that are mixed initially (Al and Cu).

- Phases:

  A phase is a homogenous, physically distinct and mechanically separable portion of the material with a given chemical composition and structure (α and β).



Phase Equilibria: Solubility Limit

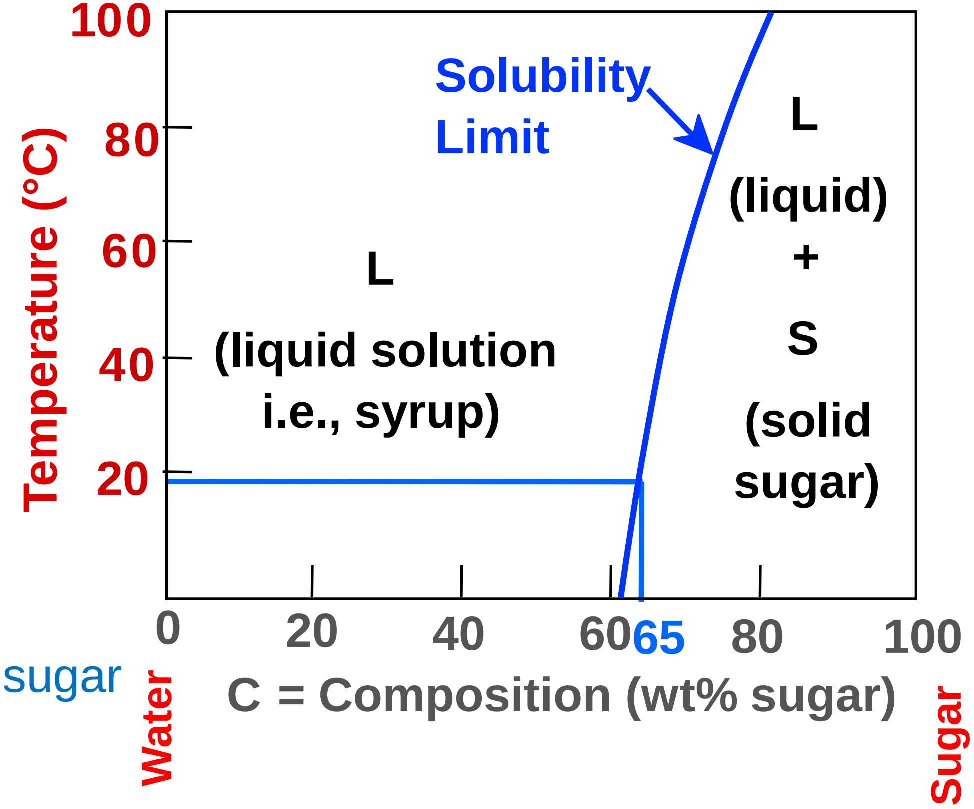
- Solution – solid, liquid, or gas solutions, single phase
- Mixture – more than one phase

- Solubility Limit:
  Maximum concentration for which only a single phase solution exists.

Question: What is the solubility limit for sugar in water at 20°C?

Answer: 65 wt% sugar.
At 20°C, if C < 65 wt% sugar: syrup
At 20°C, if C > 65 wt% sugar: syrup + sugar

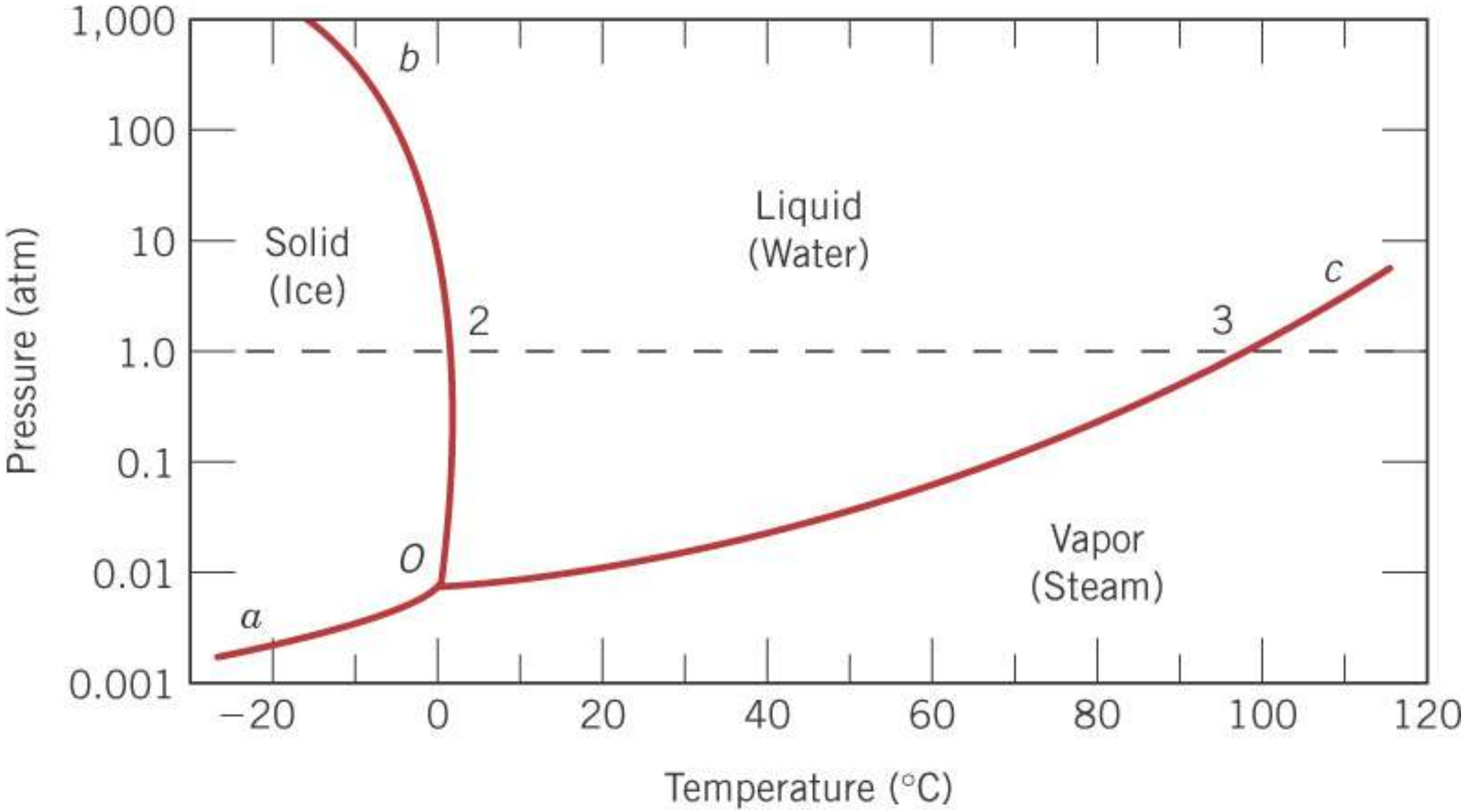
Sugar/Water Phase Diagram



Equilibrium

- A system is at equilibrium if its free energy is at a minimum, given a specified combination of temperature, pressure and composition.
- The (macroscopic) characteristics of the system do not change with time — the system is stable.
- A change in T, P or C for the system will result in an increase in the free energy and possible changes to another state whereby the free energy is lowered.

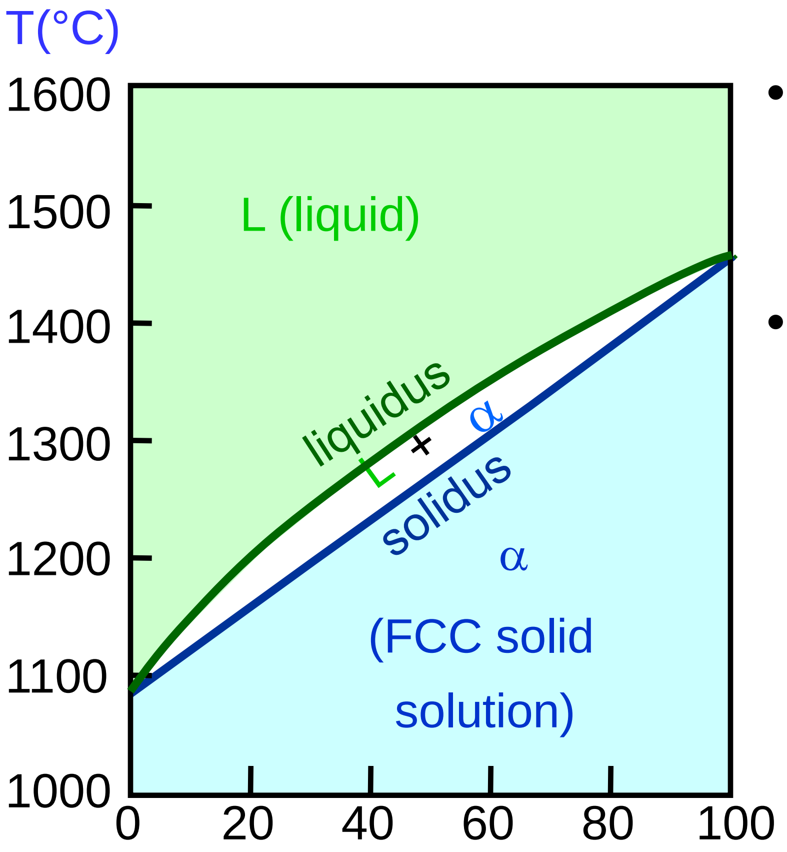
One Component Phase Diagram



Phase Diagrams

- Indicate phases as a function of Temp, Comp and Pressure.
- Focus on:
  - binary systems: 2 components.
  - independent variables: T and C (P = 1 atm is almost always used).

Cu-Ni system

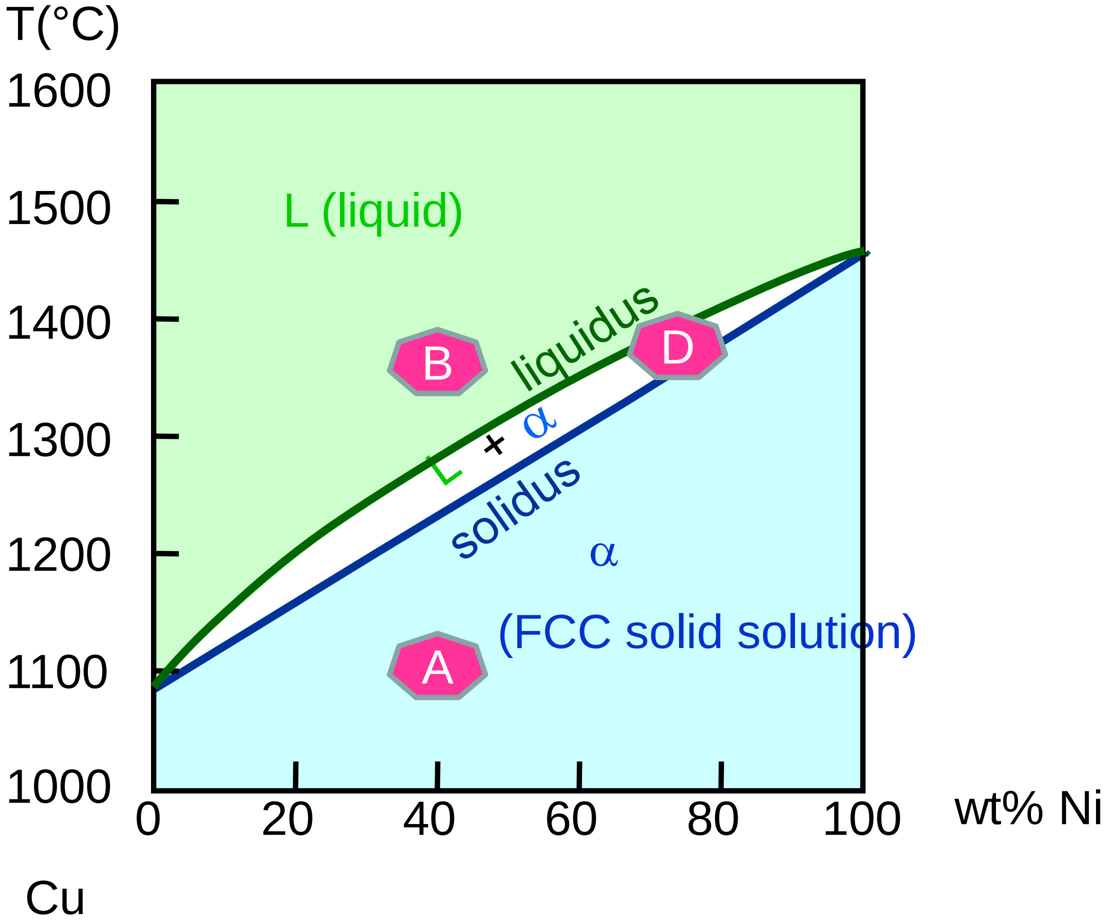


- 2 phases:
  - L (liquid)
  - α (FCC solid solution)
- 3 different phase fields:
  - L
  - L + α
  - α

Effect of Temperature & Composition (C_o)

- Changing T can change # of phases: path A to B.
- Changing C_o can change # of phases: path B to D.

Cu-Ni system



Determination of phase(s) present

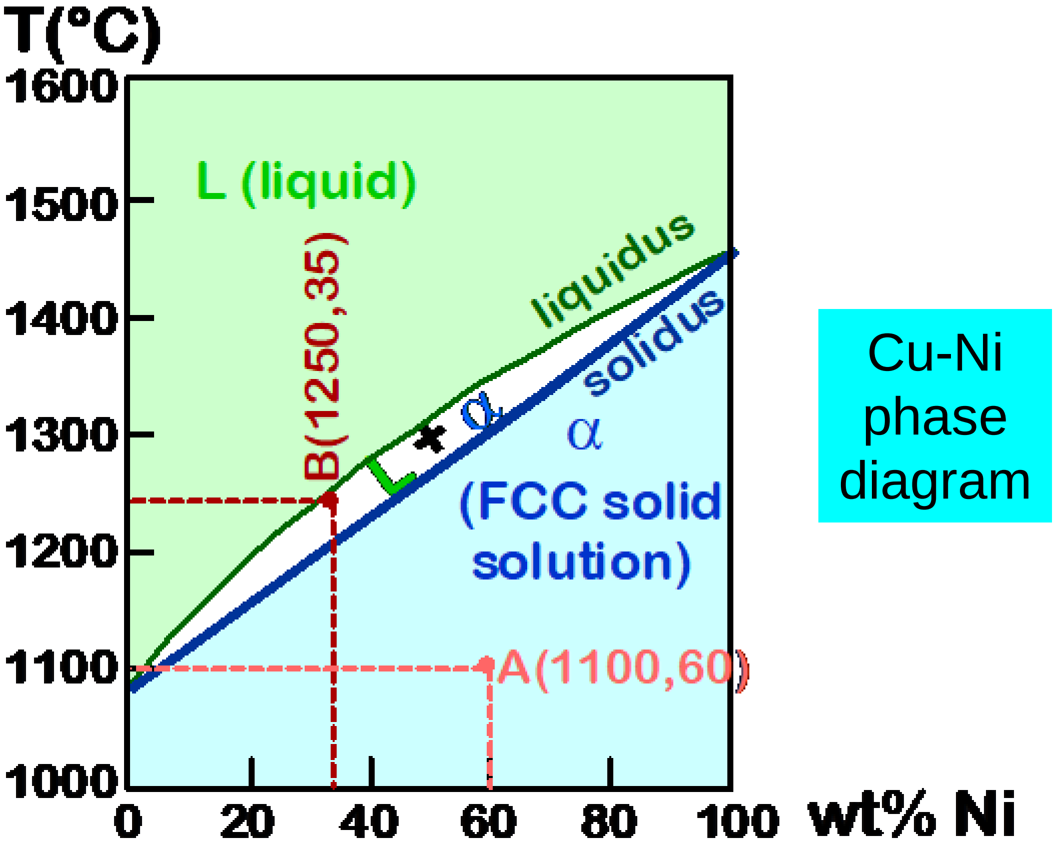
- Rule 1: If we know T and C_o, then we know:
  --how many phases and which phases are present.

- Examples:

A(1100, 60):
1 phase: α

B(1250, 35):
2 phases: L + α

Melting points: Cu = 1085°C, Ni = 1453 °C



Cu-Ni phase diagram

Solidus - Temperature where alloy is completely solid. Above this line, liquefaction begins.
Liquidus - Temperature where alloy is completely liquid. Below this line, solidification begins.

Phase Diagrams: composition of phases

- Rule 2: If we know T and C_o, then we know:
  --the composition of each phase.

- Examples:

At T_A = 1320°C:

Only Liquid (L) present

$C_L = C_0$ (= 35 wt% Ni)

At T_D = 1190°C:

Only Solid (α) present

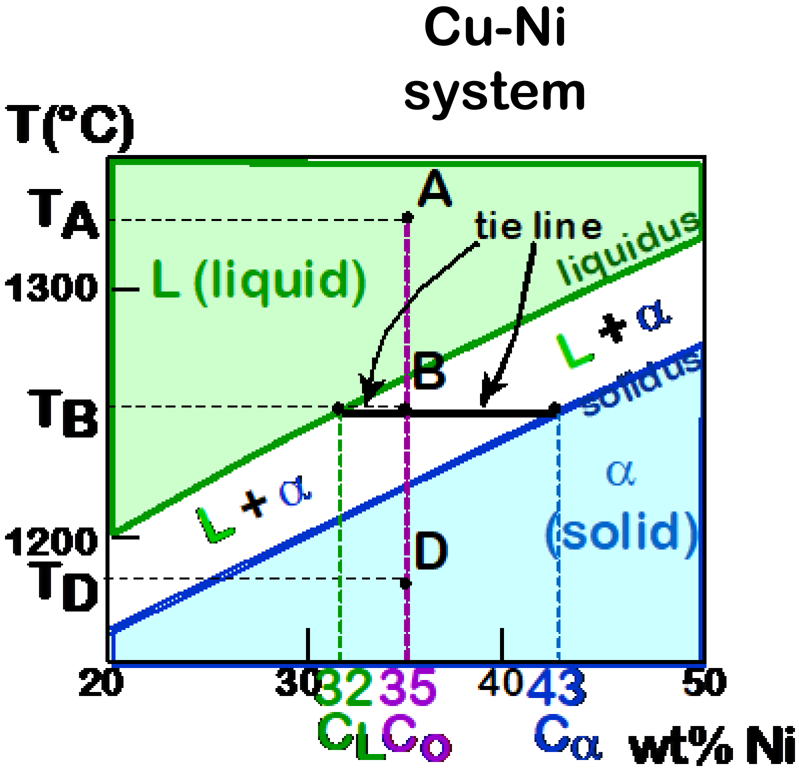
$C_\alpha = C_0$ (= 35 wt% Ni)

At T_B = 1250°C:

Both α and L present

$C_L = C_{liquidus}$ (= 32 wt% Ni)

$C_\alpha = C_{solidus}$ (= 43 wt% Ni)



Phase Diagrams: weight fractions of phases

- Rule 3: If we know T and C_o, then we know:
  --the amount of each phase (given in wt%).
- **Examples:**

C_o = 35wt%Ni

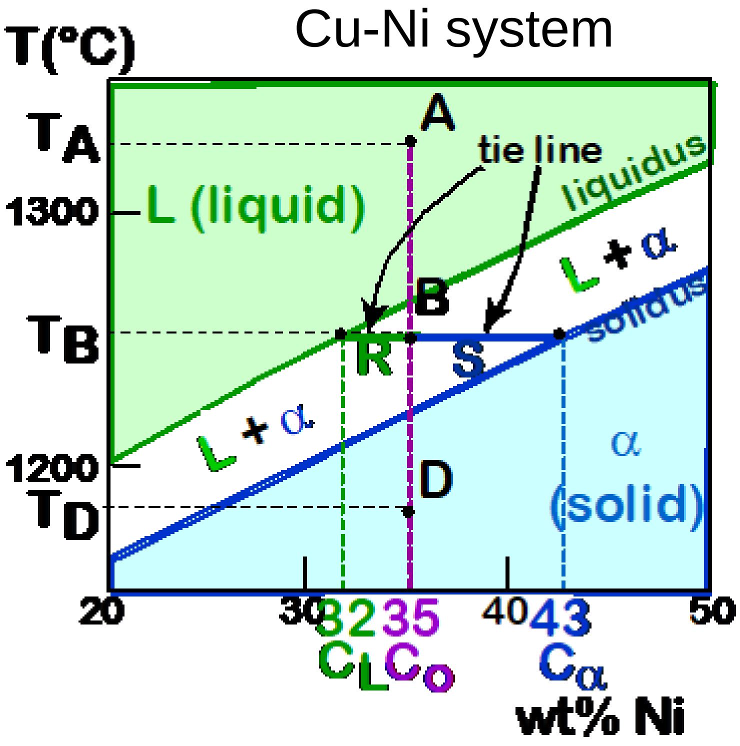
At T_A: Only Liquid (L)

W_L = 100wt%, W_α = 0

At T_D: Only Solid (α)

W_L = 0, W_α = 100wt%

At T_B: Both α and L

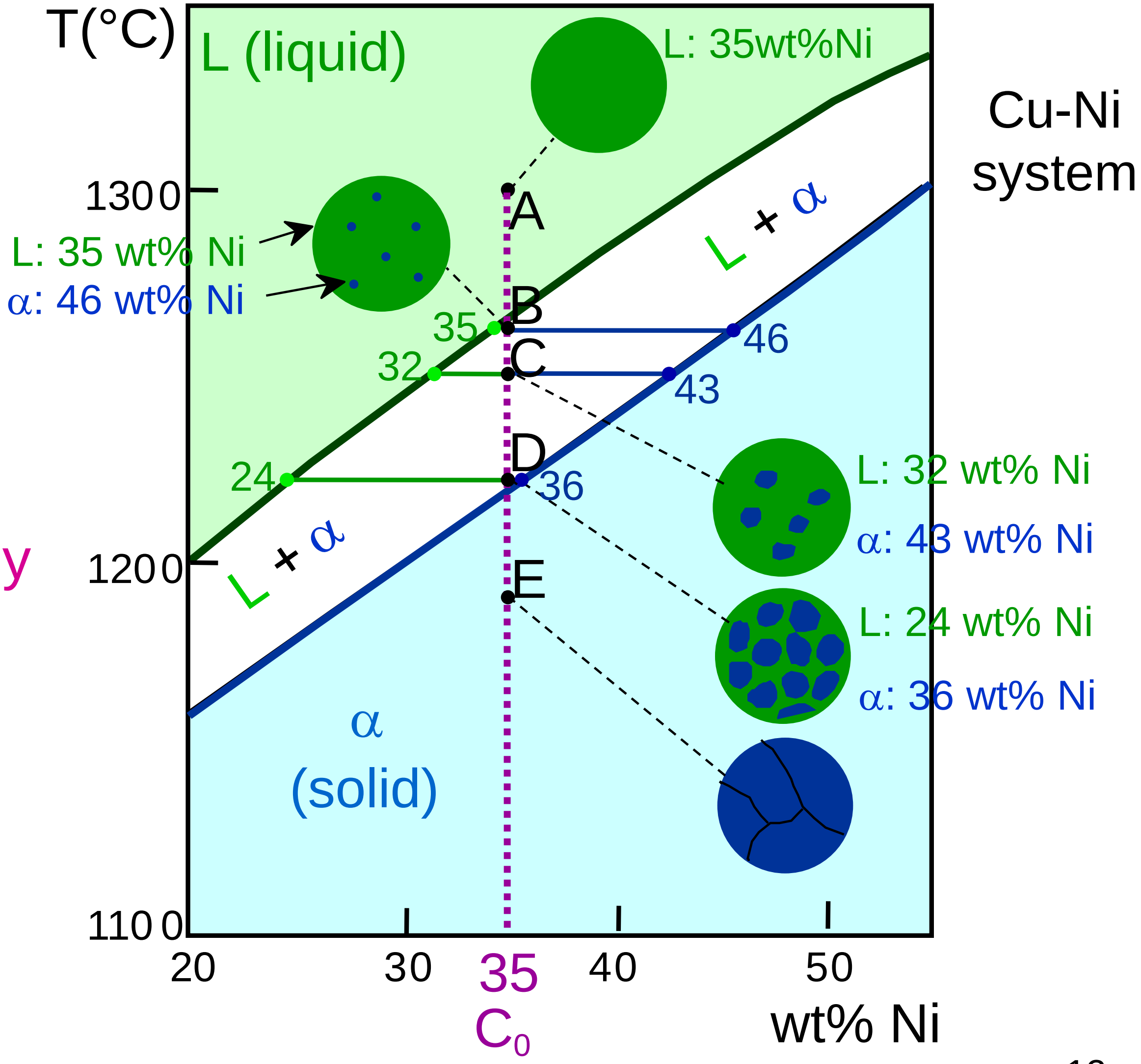

Cu-Ni system

$$W_L = \frac{C_\alpha - C_o}{C_\alpha - C_L} = \frac{43-35}{43-32} = 73\text{wt }\%$$

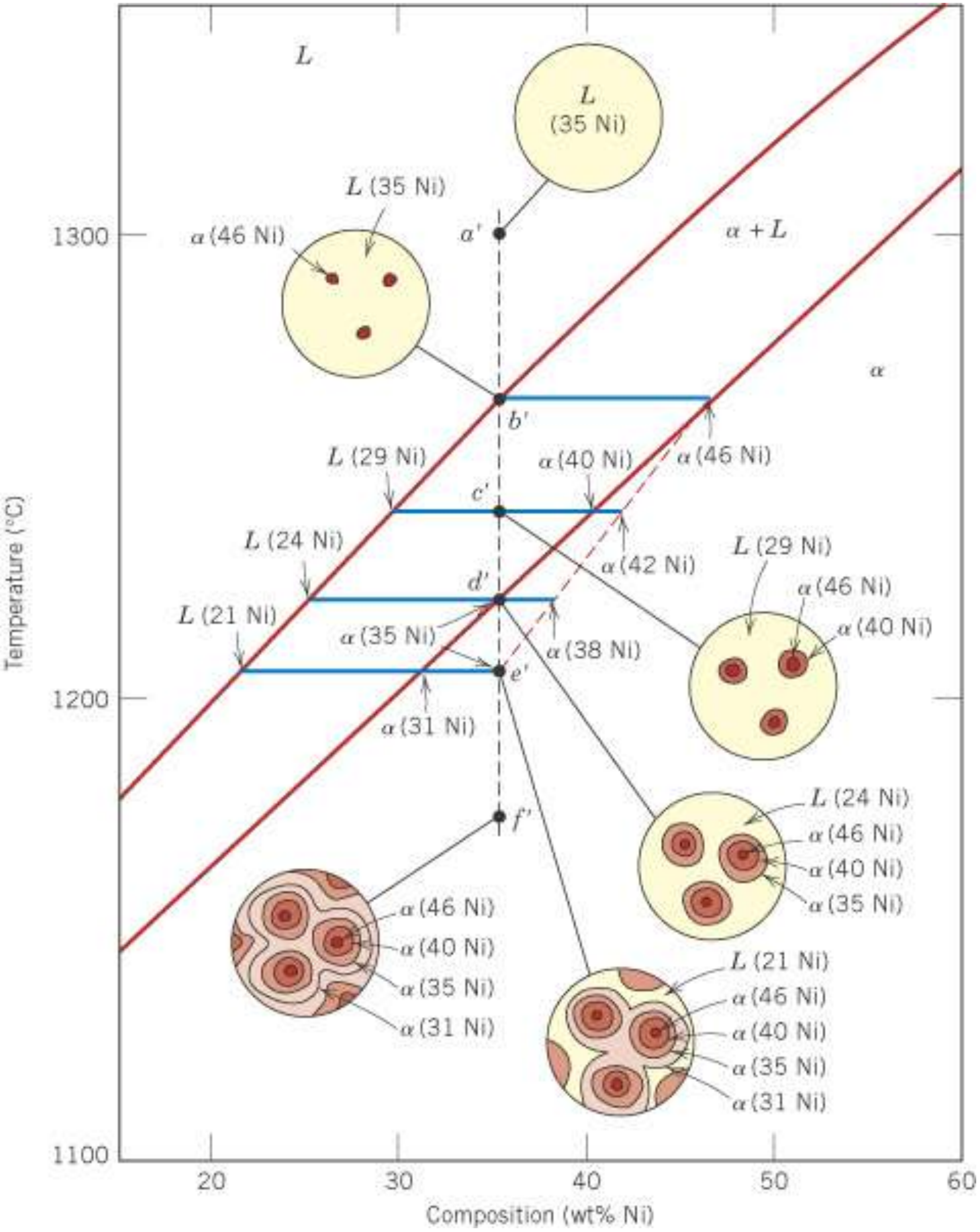
$$W_\alpha = \frac{C_o - C_L}{C_\alpha - C_L} = 27\text{wt }\%$$

Ex: Equilibrium Cooling of a Cu-Ni Alloy

- Phase diagram:
  Cu-Ni system.
- Consider microstuctural changes that accompany the cooling of a
  C_0 = 35 wt% Ni alloy



- Development of microstructure during the non-equilibrium solidification of a 35 wt% Ni-65 wt% Cu alloy outcome:
- Segregation-nonuniform distribution of elements within grains.
- Weaker grain boundaries if alloy is reheated.

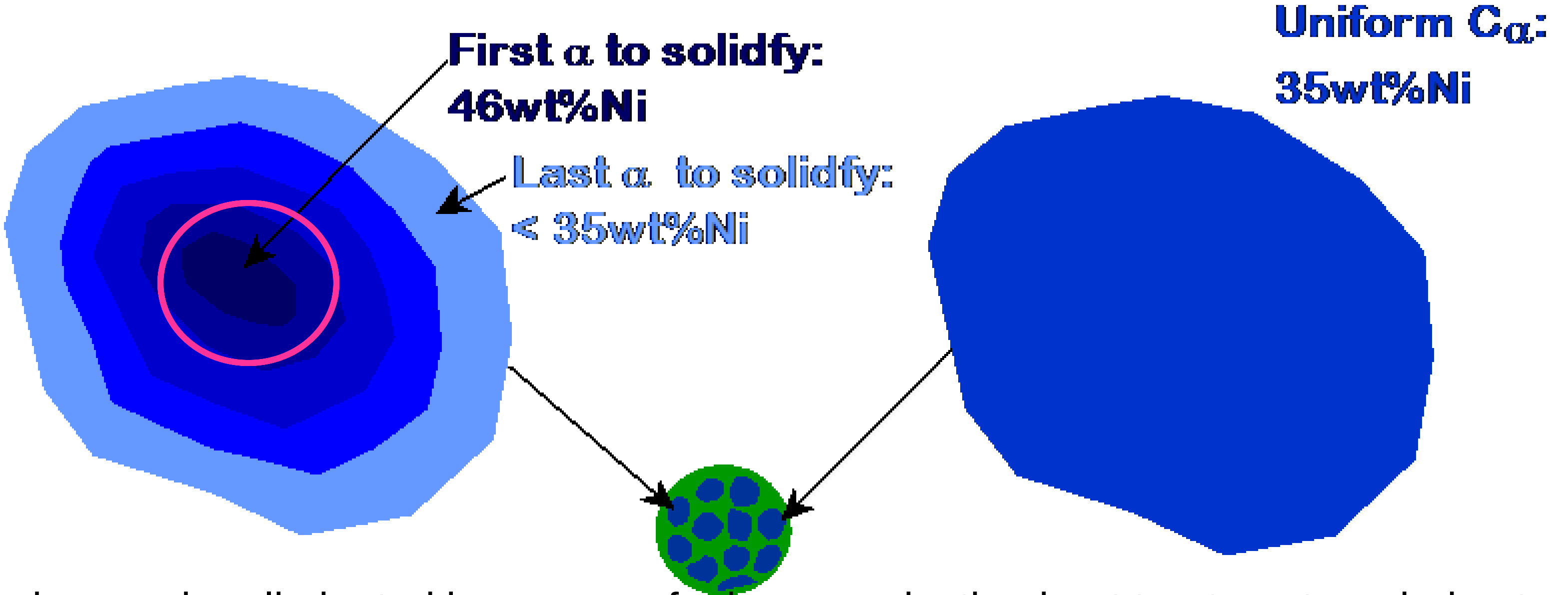


Cored vs Equilibrium Phases

- **C_α** changes as it solidifies.
- Cu-Ni case: First α to solidify has **C_α** = 46wt%Ni.
  Last α to solidify has **C_α** = 35wt%Ni.

- Fast rate of cooling:
  Cored structure

- Slow rate of cooling:
  Equilibrium structure

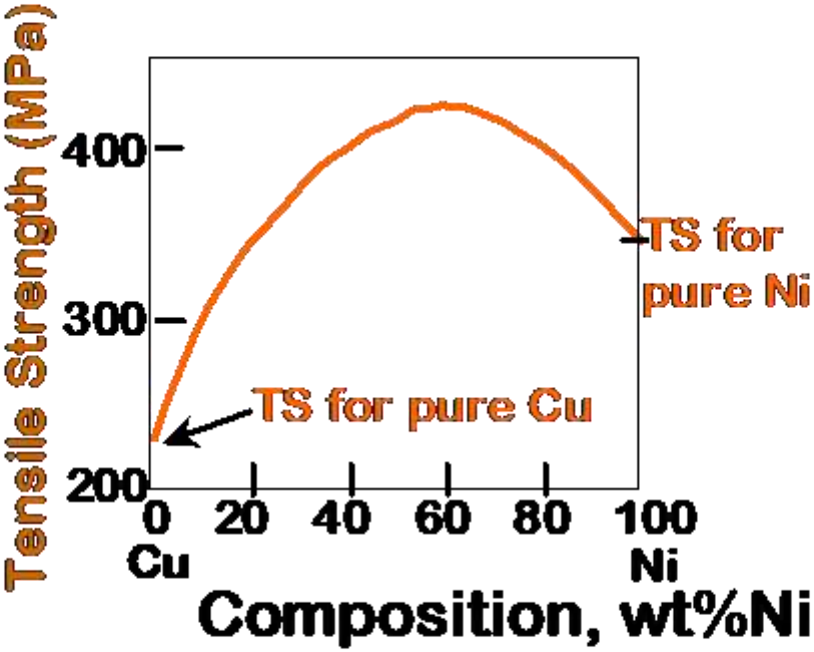


- Coring can be eliminated by means of a homogenization heat treatment carried out at temperatures below the alloy’s solidus. During the process, atomic diffusion produces grains that are compositionally homogeneous.

Mechanical Properties: Cu-Ni System

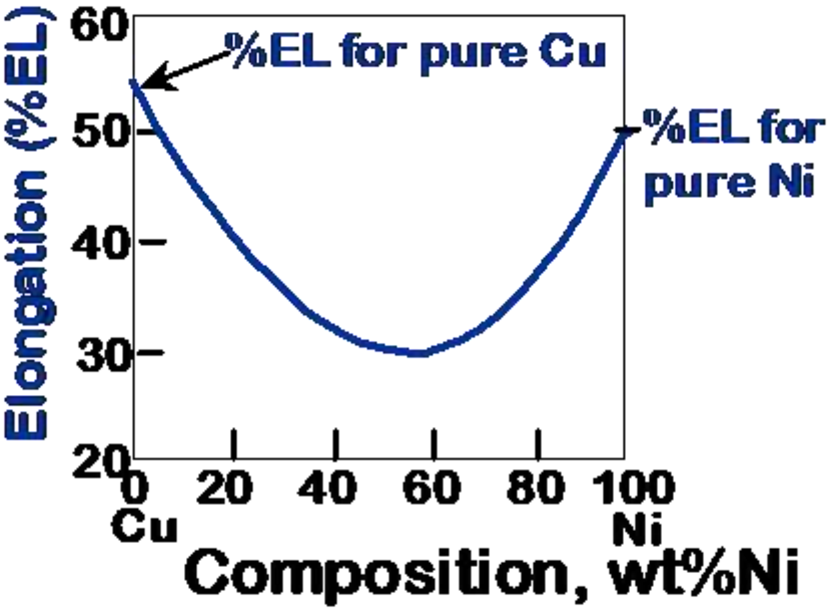
- Effect of solid solution strengthening on:

--Tensile strength (TS)



--Peak as a function of C_o

--Ductility (%EL,%AR)

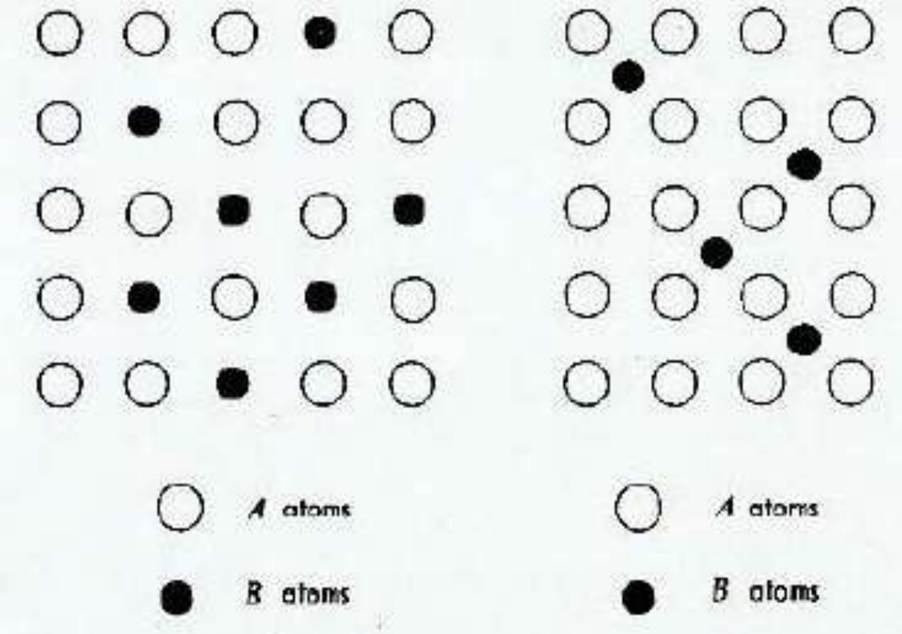


--Min. as a function of C_o

Binary Isomorphous Systems

Cu-Ni system:

- The liquid L is a homogeneous liquid solution composed of Cu and Ni.
- The α phase is a substitutional solid solution consisting of Cu and Ni atoms with an FCC crystal structure.
- At temperatures below 1080 C, Cu and Ni are mutually soluble in each other in the solid state for all compositions.
- The complete solubility is explained by their FCC structure, nearly identical atomic radii and electro-negativities, and similar valences.
- The Cu-Ni system is termed isomorphous because of this <u>complete liquid and solid solubility of the 2 components</u>.



What is a solid solution?

When foreign atoms are incorporated into a crystal structure, whether in substitutional or interstitial sites, the resulting phase is a solid solution of the matrix material (solvent) and the foreign atoms (solute)

Substitutional Solid Solution: Foreign (solute) atoms occupy "normal" lattice sites occupied by matrix (solvent) atoms, e.g. Cu-Ni;Ge-Si

Interstitial Solid Solutions: Foreign (solute) atoms occupy interstitial sites, e.g., Fe-C

Criteria for Solid Solubility

Simple system (e.g., Ni-Cu solution)

	Crystal Structure	electroneg	r (nm)
Ni	FCC	1.9	0.1246
Cu	FCC	1.8	0.1278

- Both have the same crystal structure (FCC) and have similar electronegativities and atomic radii (W. Hume – Rothery rules) suggesting high mutual solubility.
- Ni and Cu are totally soluble in one another for all proportions.

Isomorphous Binary Phase Diagram

- Phase diagram:

  Cu-Ni system.

- System is:

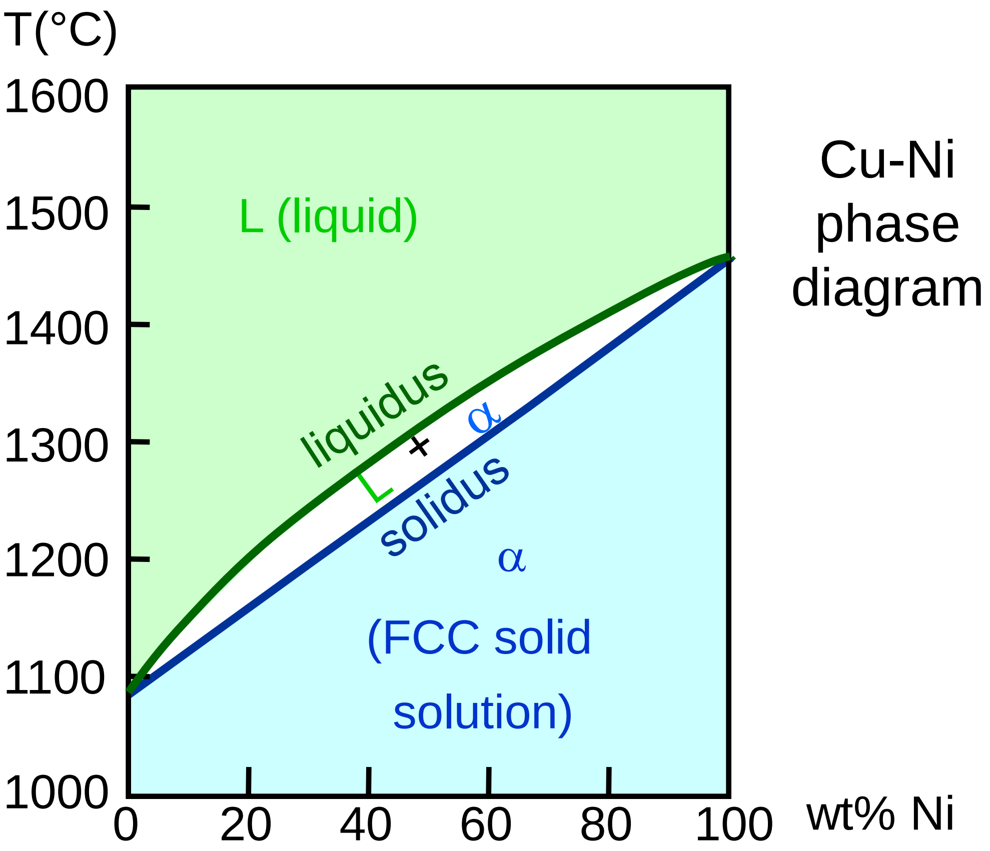
  -- binary

  2 components:

  Cu and Ni.

  -- isomorphous

  i.e., complete solubility of one component in another; α phase field extends from 0 to 100 wt% Ni.



Cu-Ni phase diagram

Importance of Phase Diagrams

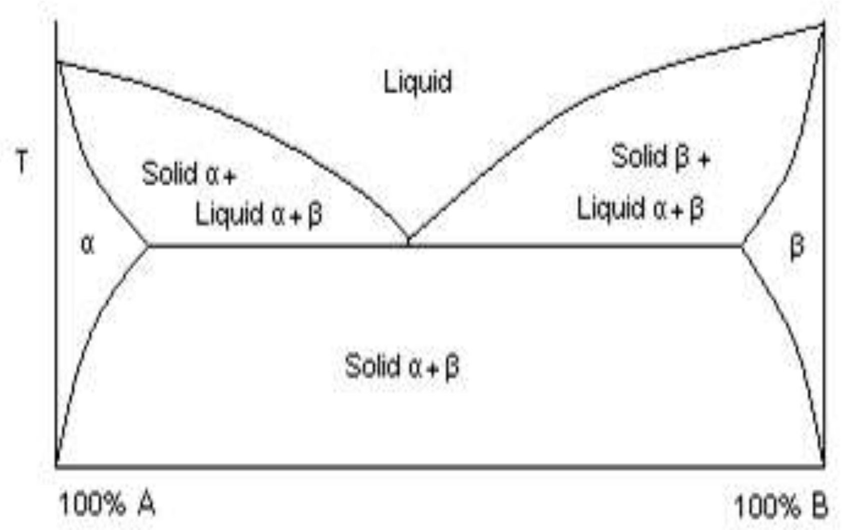
- There is a strong correlation between microstructure and mechanical properties, and the development of alloy microstructure is related to the characteristics of its phase diagram.
- Phase diagrams provide valuable information about melting, casting, crystallization and other phenomena.

Microstructure

- In metal alloys, microstructure is characterized by the number of phases, their proportions, and the way they are arranged.
- The microstructure depends on:
  - Alloying elements
  - Concentration
  - Heat treatment (temperature, time, rate of cooling)

Eutectic

- A **eutectic** or **eutectic mixture** is a mixture of two or more phases at a composition that has the lowest melting point.
- It is where the phases simultaneously crystallize from molten solution.
- The proper ratios of phases to obtain a eutectic is identified by the eutectic point on a binary phase diagram.
- The term comes from the Greek 'eutektos', meaning 'easily melted.‘



- The phase diagram displays a simple binary system composed of two components, **A** and **B**, which has a eutectic point.
- The phase diagram plots relative concentrations of A and B along the X-axis, and temperature along the Y-axis. **The eutectic point is the point where the liquid phase borders directly on the solid α + β phase; it** represents the minimum melting temperature of any possible A B alloy.
- The temperature that corresponds to this point is known as the **eutectic temperature**.
- Not all binary system alloys have a eutectic point: those that form a solid solution at all concentrations, such as the gold-silver system, have no eutectic. An alloy system that has a eutectic is often referred to as a eutectic system, or eutectic alloy.
- Solid products of a eutectic transformation can often be identified by their lamellar structure, as opposed to the dendritic structures commonly seen in non-eutectic solidification. The same conditions that force the material to form lamellae can instead form an amorphous solid if pushed to an extreme.

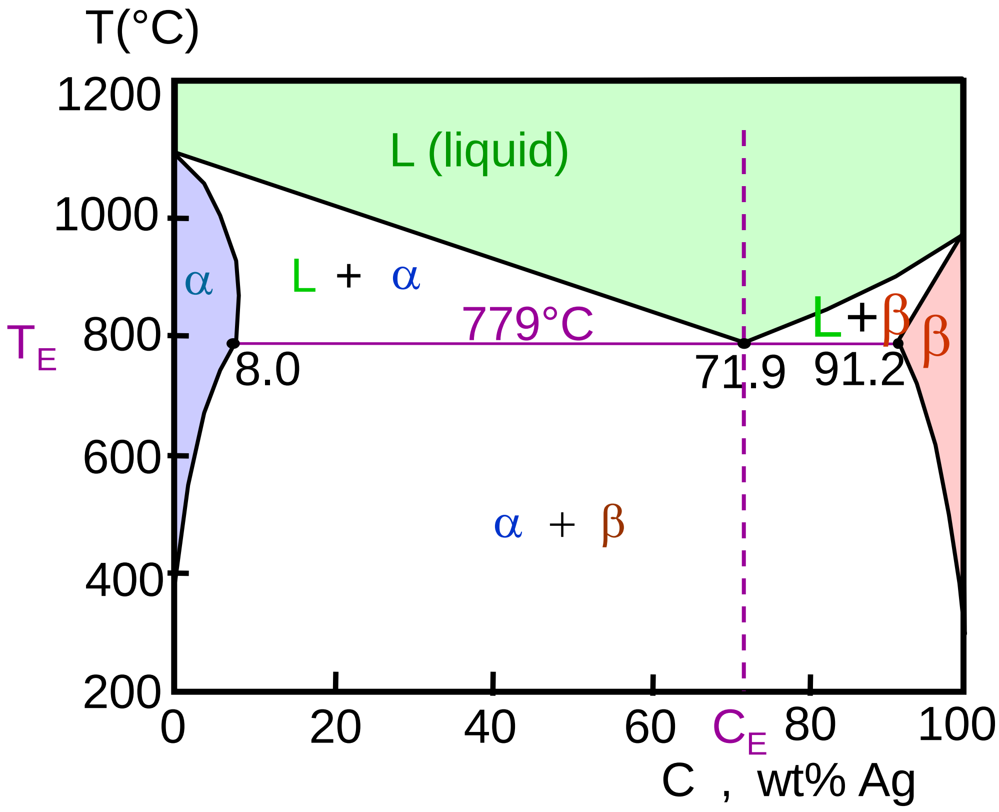
Binary-Eutectic Systems

2 components

has a special composition
with a min. melting T.

Cu-Ag system

- 3 single phase regions
  (L, α, β)
- Limited solubility:
  α: mostly Cu
  β: mostly Ag
- T_E : No liquid below T_E
- C_E : Composition at
  temperature T_E

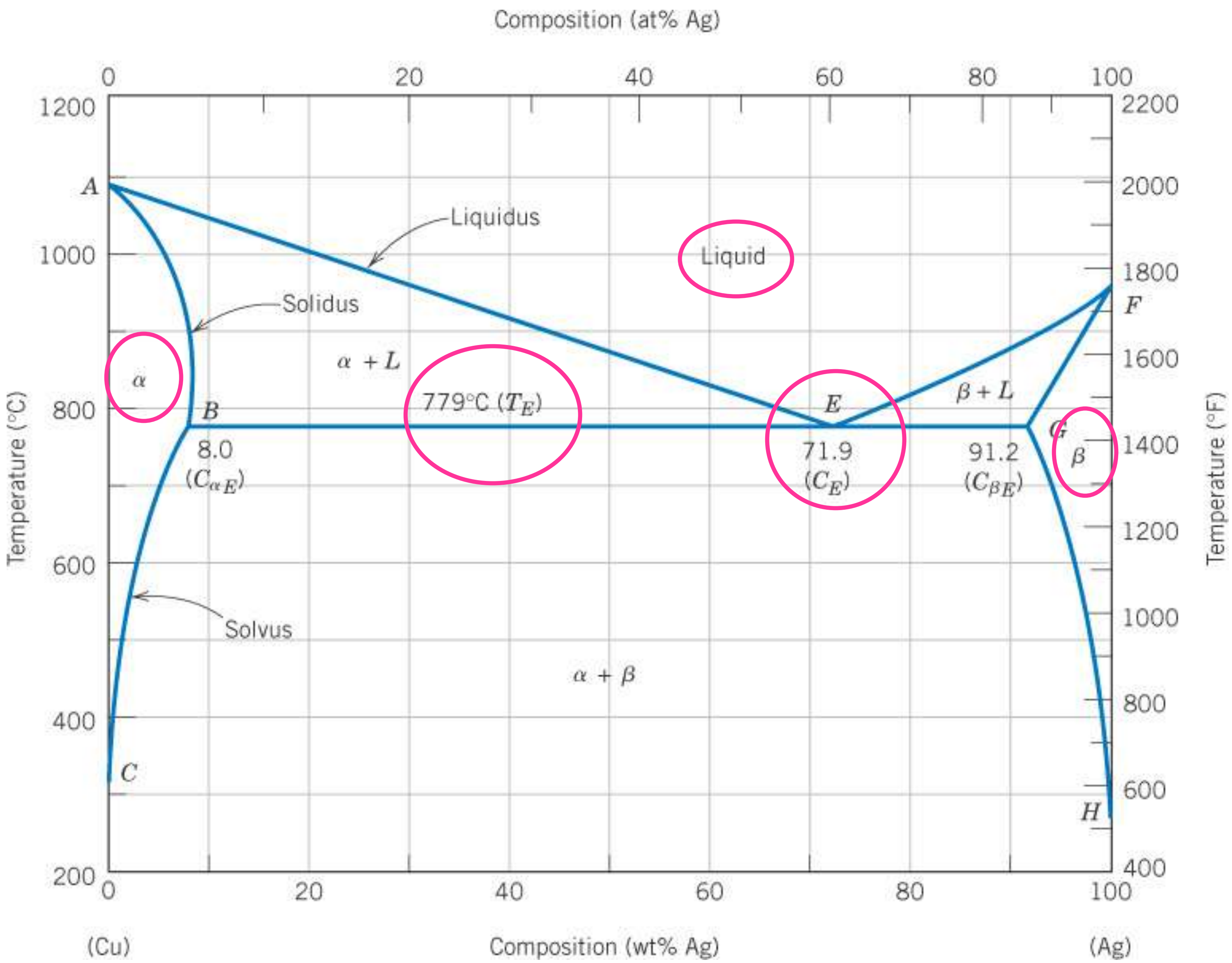


- **Eutectic reaction**

$$L(C_E) \rightleftharpoons \alpha(C_{\alpha E}) + \beta(C_{\beta E})$$

$$L(71.9\text{ wt\% Ag}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(8.0\text{ wt\% Ag}) + \beta(91.2\text{ wt\% Ag})$$

Copper-Silver Phase Diagram



Eutectic Reaction

- Solvus – (solid solubility line) BC, GH
- Solidus – AB, FG, BEG (eutectic isotherm)
- Liquidus – AEF
- Maximum solubility: α = 8.0 wt% Ag, β = 8.8 wt %Cu
- Invariant point (where 3 phases are in equilibrium) is at E; C_E = 71.9 wt% Ag, T_E = 779C (1434F).

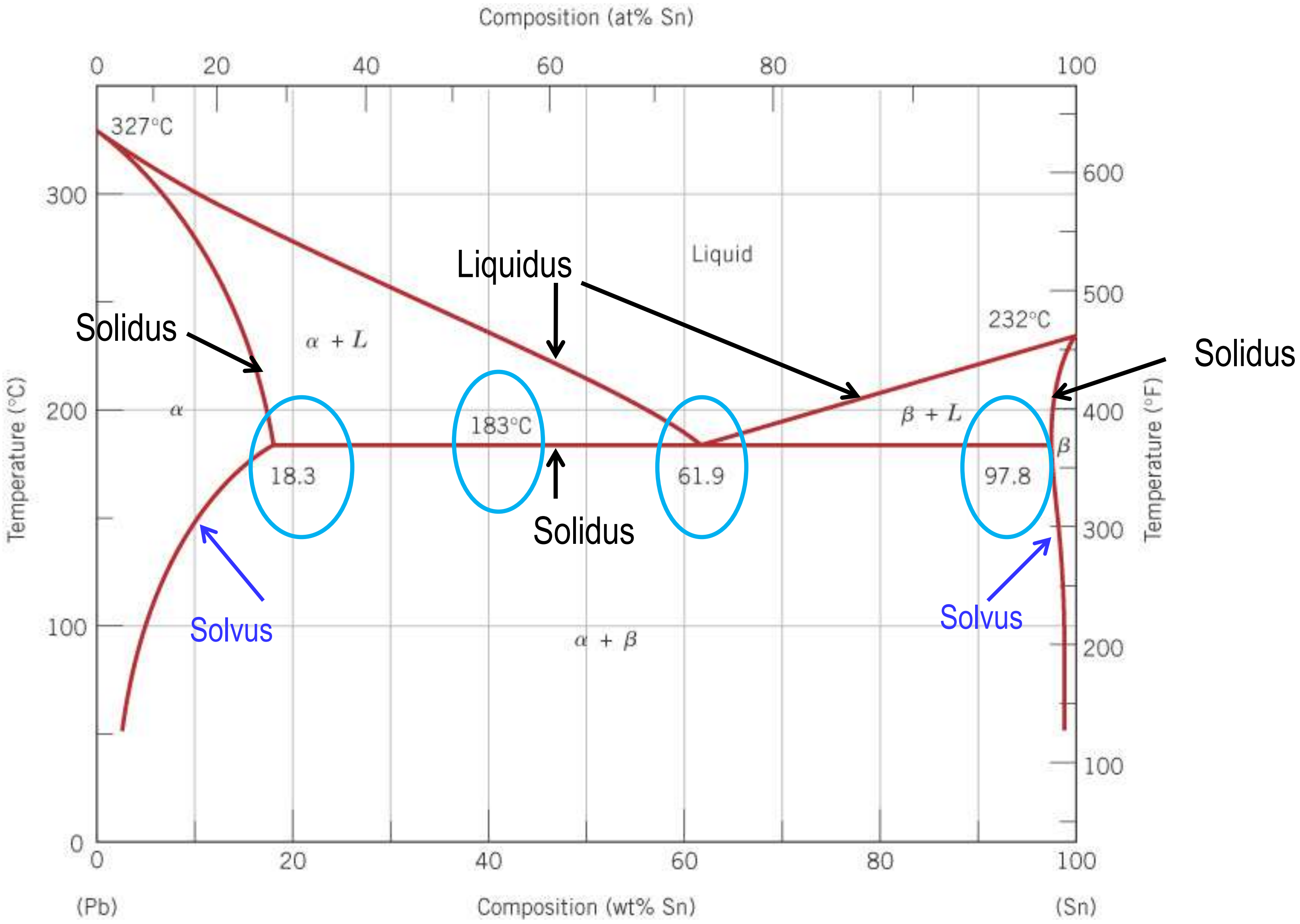
- An isothermal, reversible reaction between two (or more) solid phases during the heating of a system where a single liquid phase is produced.

Eutectic reaction

$$L(C_E) \rightleftharpoons \alpha(C_{\alpha E}) + \beta(C_{\beta E})$$

$$L(71.9\text{ wt\% Ag}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(8.0\text{ wt\% Ag}) + \beta(91.2\text{ wt\% Ag})$$

Pb-Sn Phase Diagram



Solidification of Eutectic Mixtures

- Mixtures of some metals, such as copper & nickel, are completely soluble in both liquid and solid states for all concentrations of both metals. Copper & nickel have the same crystal structure (FCC) and have nearly the same atomic radii. The solid formed by cooling can have any proportion of copper & nickel. Such completely miscible mixtures of metals are called **isomorphous**.

- By contrast, a mixture of lead & tin that is **eutectic** is only partially soluble when in the solid state. Lead & tin have different crystal structures (FCC versus BCT) and lead atoms are much larger. No more than 18.3 weight % solid tin can dissolve in solid lead and no more than 2.2% of solid lead can dissolve in solid tin (according to previous phase diagram).
- The solid lead-tin alloy consists of a mixture of two solid phases, one consisting of a maximum of 18.3 wt% tin (the **alpha** phase) and one consisting of a maximum of 2.2 wt% lead (the **beta** phase).

(Ex 1) Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 150°C, determine:

  -- the phases present

Answer: $\alpha + \beta$

-- the phase compositions

Answer: C_α = 11 wt% Sn

C_β = 99 wt% Sn

-- the relative amount of each phase

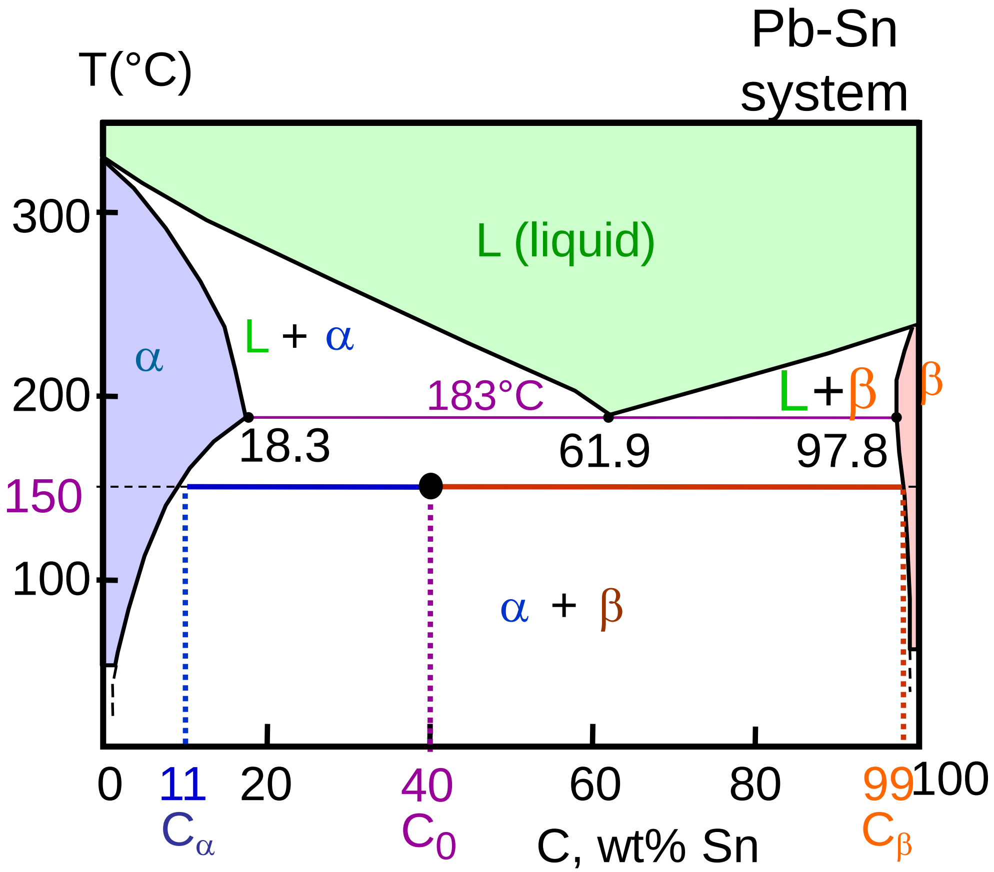
Answer:

$$W_\alpha = \frac{C_\beta - C_0}{C_\beta - C_\alpha}$$

$$= \frac{99 - 40}{99 - 11} = \frac{59}{88} = 0.67$$

$$W_\beta = \frac{C_0 - C_\alpha}{C_\beta - C_\alpha}$$

$$= \frac{40 - 11}{99 - 11} = \frac{29}{88} = 0.33$$



(Ex 2) Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 220°C, determine:
  - -- the phases present:

Answer: α + L

-- the phase compositions

Answer: C_α = 17 wt% Sn

C_L = 46 wt% Sn

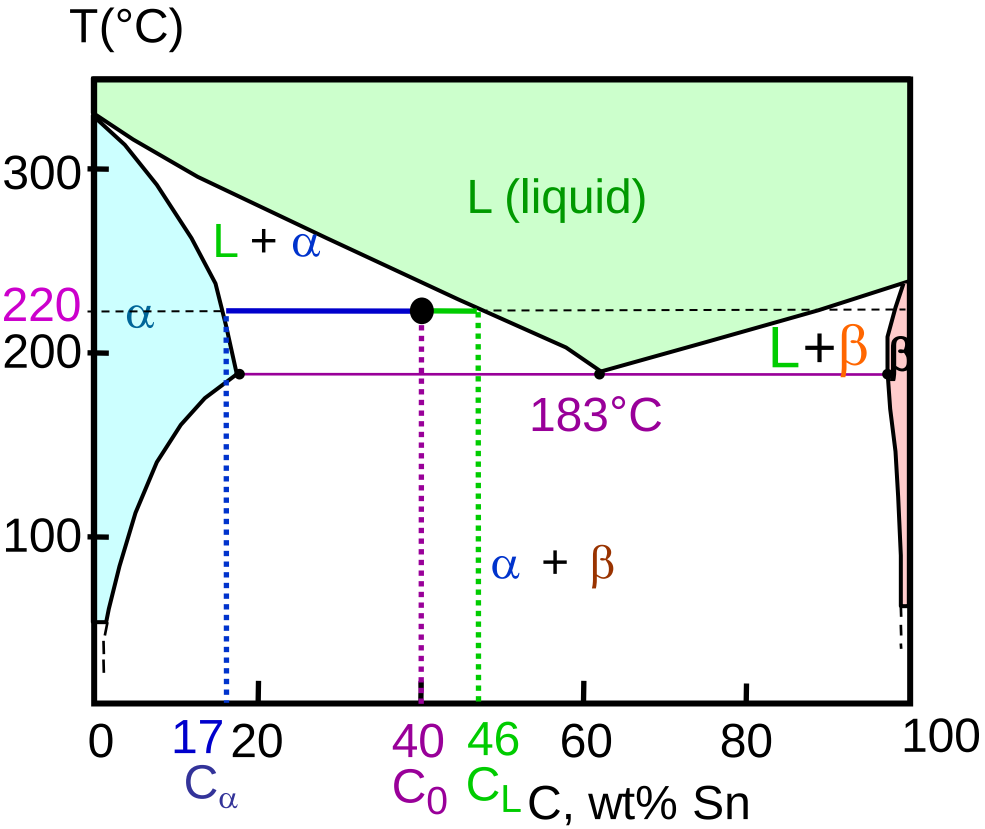
-- the relative amount of each phase

Answer:

$$W_\alpha = \frac{C_L - C_0}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17}$$

$$= \frac{6}{29} = 0.21$$

$$W_L = \frac{C_0 - C_\alpha}{C_L - C_\alpha} = \frac{23}{29} = 0.79$$



Pb-Sn

- For lead & tin the eutectic composition is 61.9 wt% tin and the eutectic temperature is 183ºC -- which makes this mixture useful as **solder**.
- At 183ºC, compositions of greater than 61.9 wt% tin result in precipitation of a tin-rich solid in the liquid mixture, whereas compositions of less than 61.9 wt% tin result in precipitation of lead-rich solid.

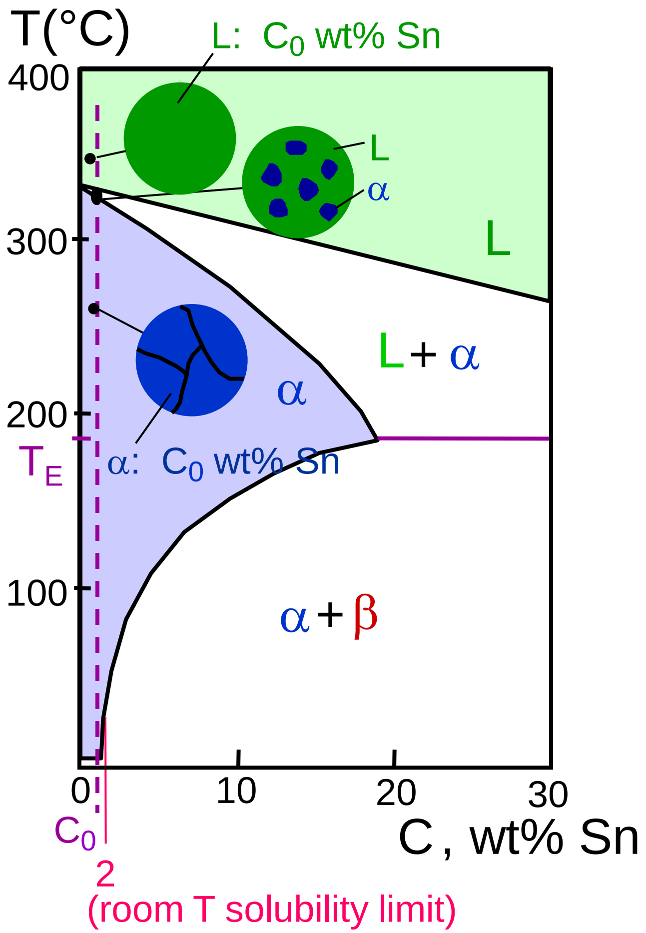
Microstructural Developments in Eutectic Systems - I

- For alloys where

  $C_0 < 2$ wt% Sn

- Result at room temperature is a polycrystalline with grains of α phase having composition C_0

Pb-Sn system

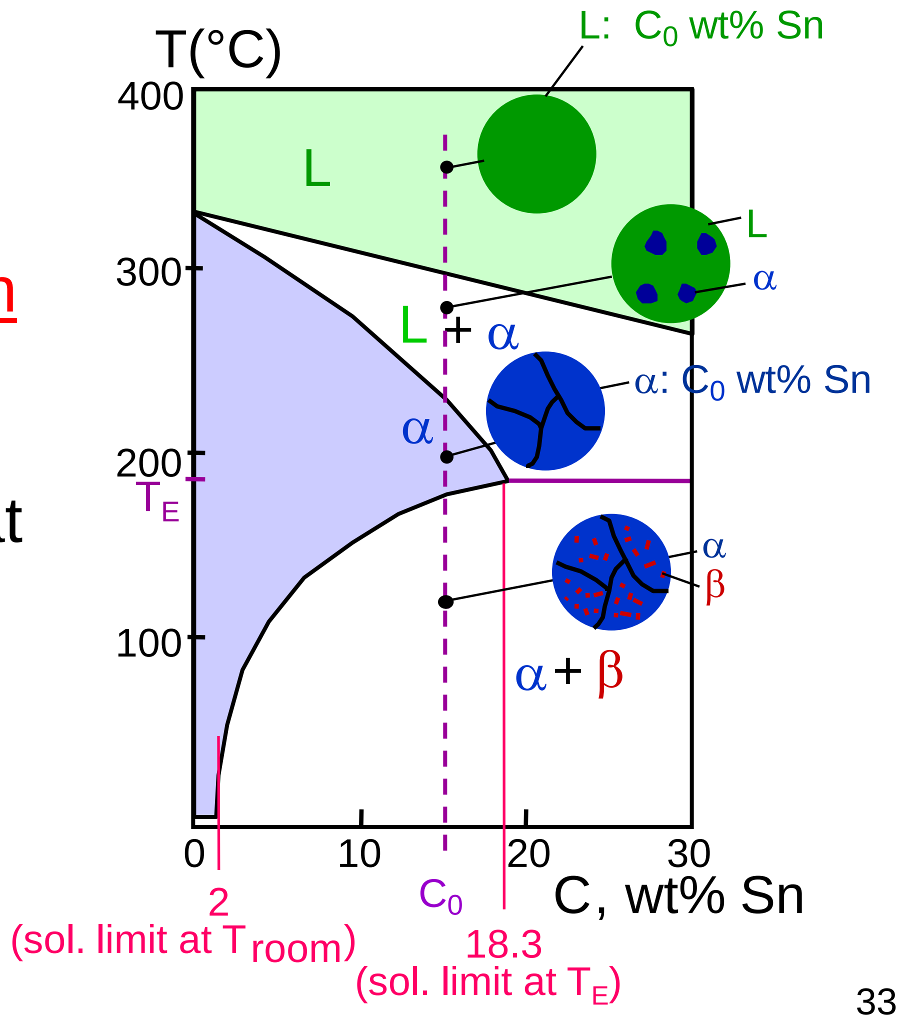


Microstructural Developments in Eutectic Systems - II

Pb-Sn system

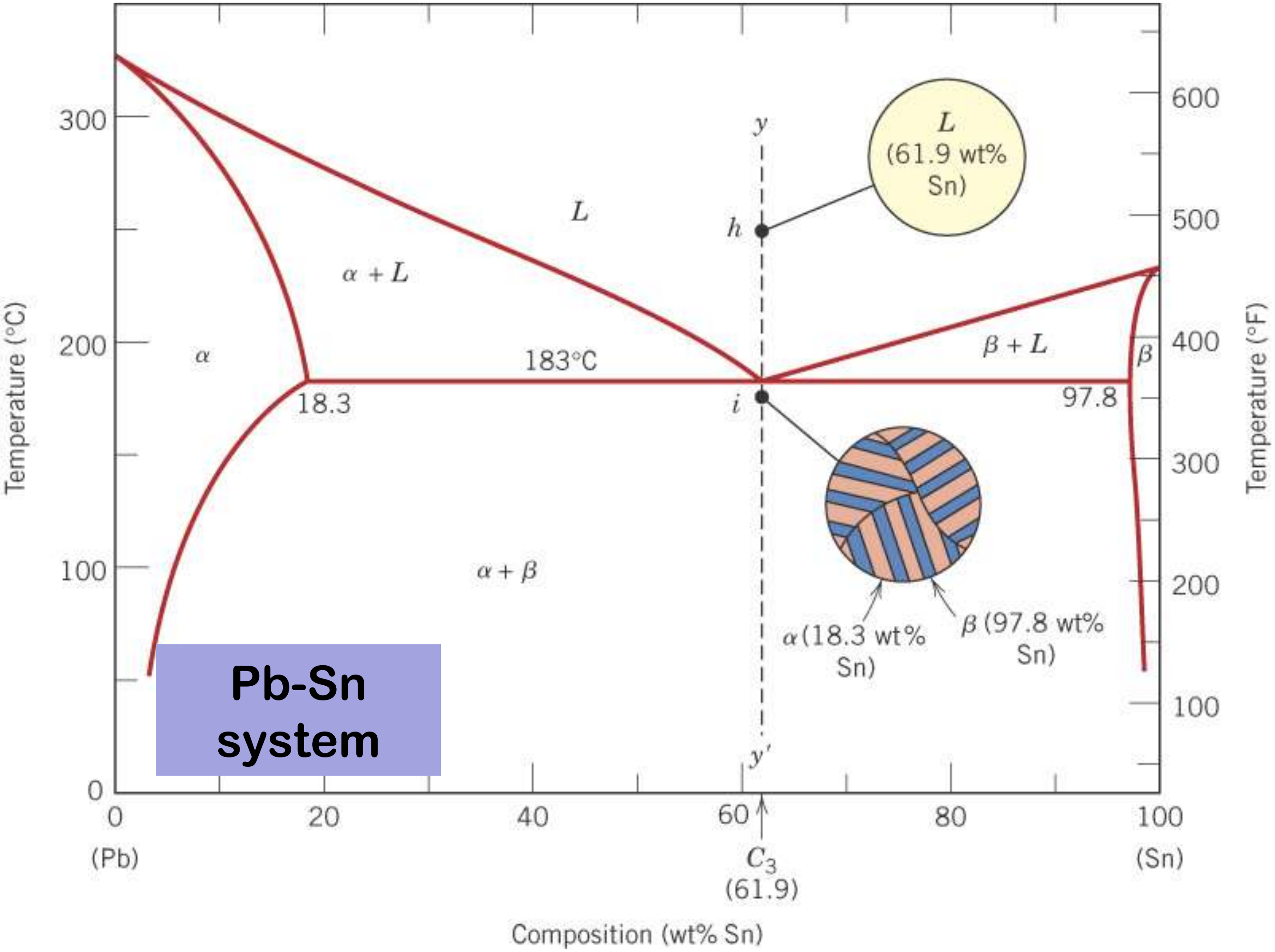
2 wt% Sn < C_0 < 18.3 wt% Sn

- Results in polycrystalline microstructure with α grains and small β-phase particles at lower temperatures.



Microstructures in Eutectic Systems - III

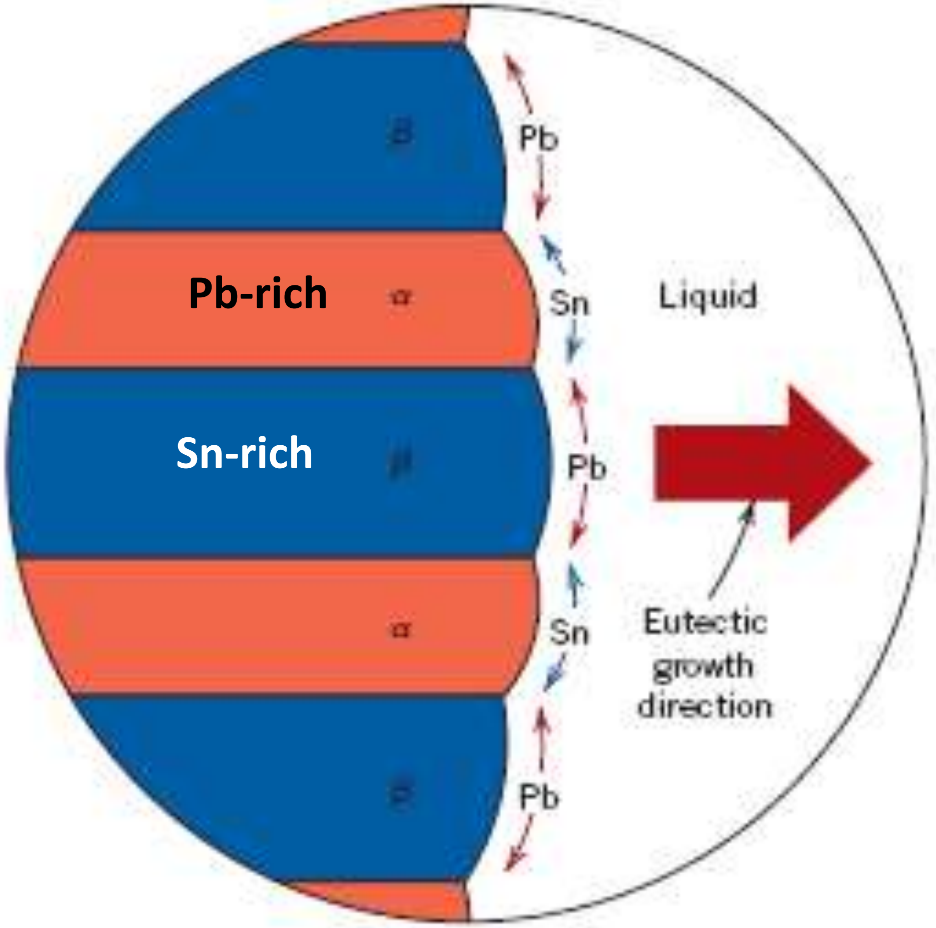
- $C_o = C_E$
- Results in a eutectic microstructure with alternating layers of α and β crystals.



$$L(61.9\ \text{wt\% Sn}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(18.3\ \text{wt\% Sn}) + \beta(97.8\ \text{wt\% Sn})$$

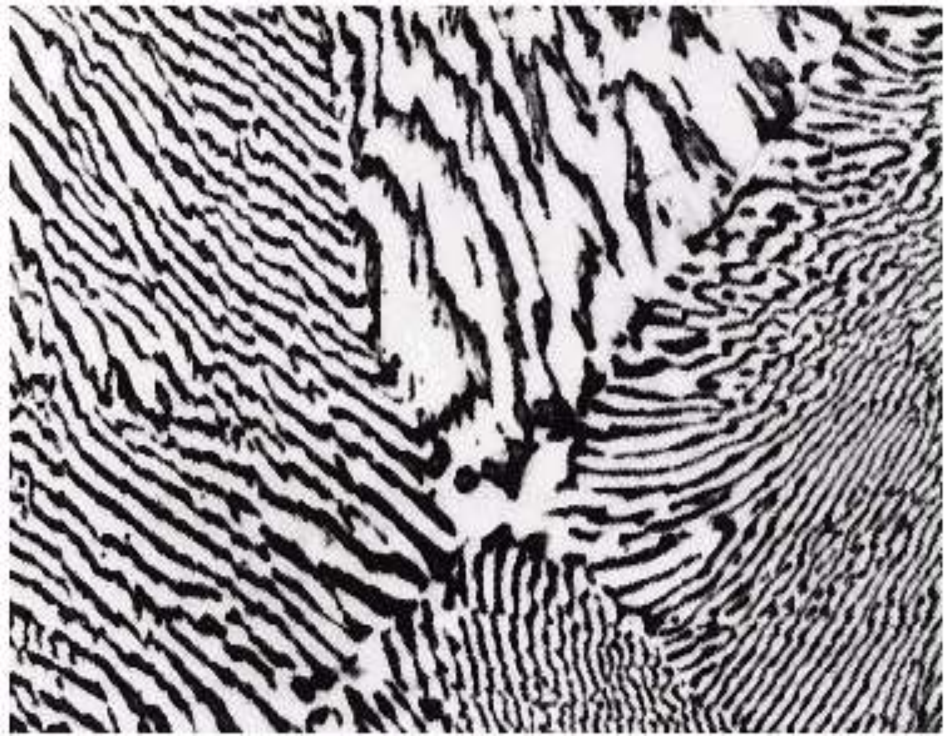
Lamellar Eutectic Structure

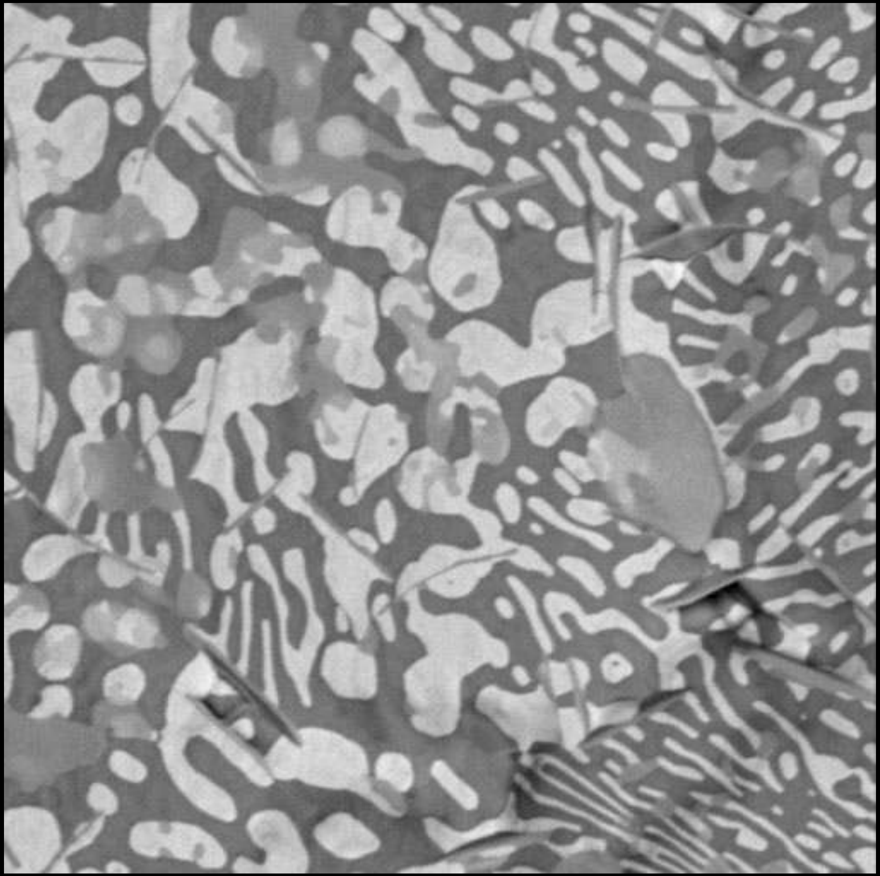
- A 2-phase microstructure resulting from the solidification of a liquid having the eutectic composition where the phases exist as a lamellae that alternate with one another.
- Formation of eutectic layered microstructure in the Pb-Sn system during solidification at the eutectic composition. Compositions of α and β phases are very different. Solidification involves redistribution of Pb and Sn atoms by **atomic diffusion**.

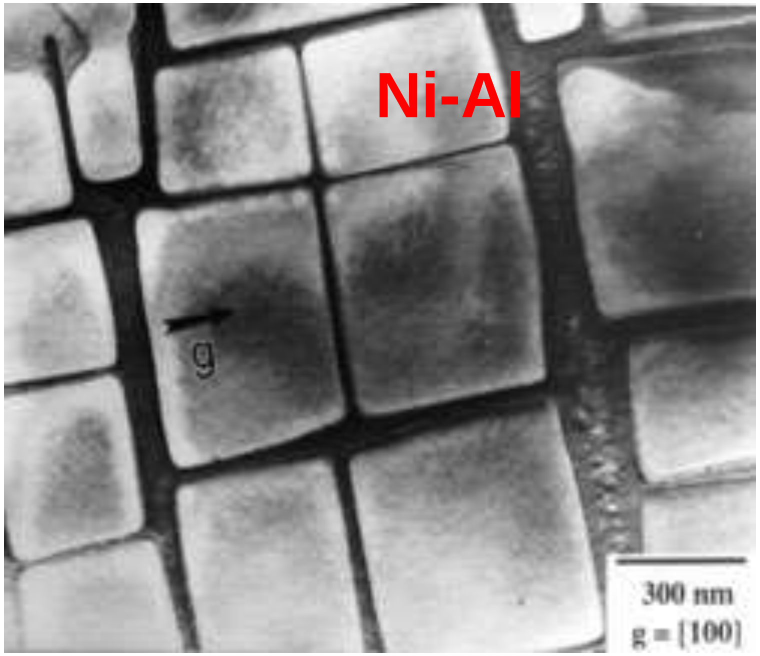


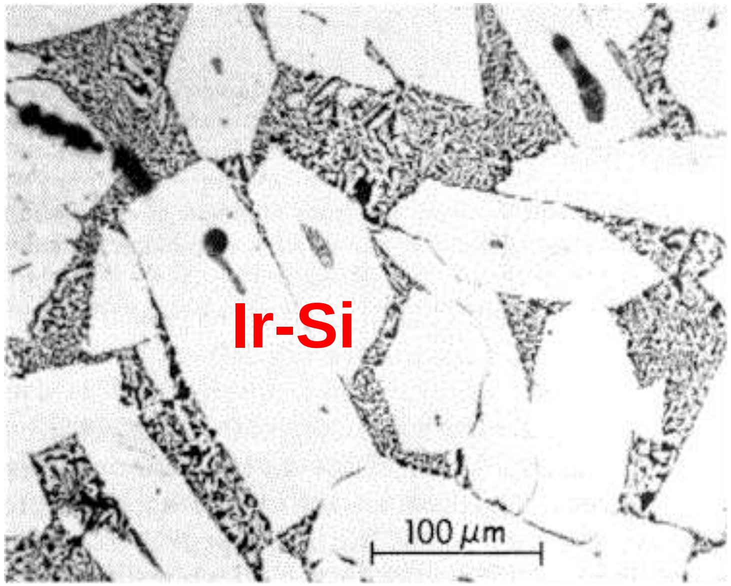
Pb-Sn Microstructures

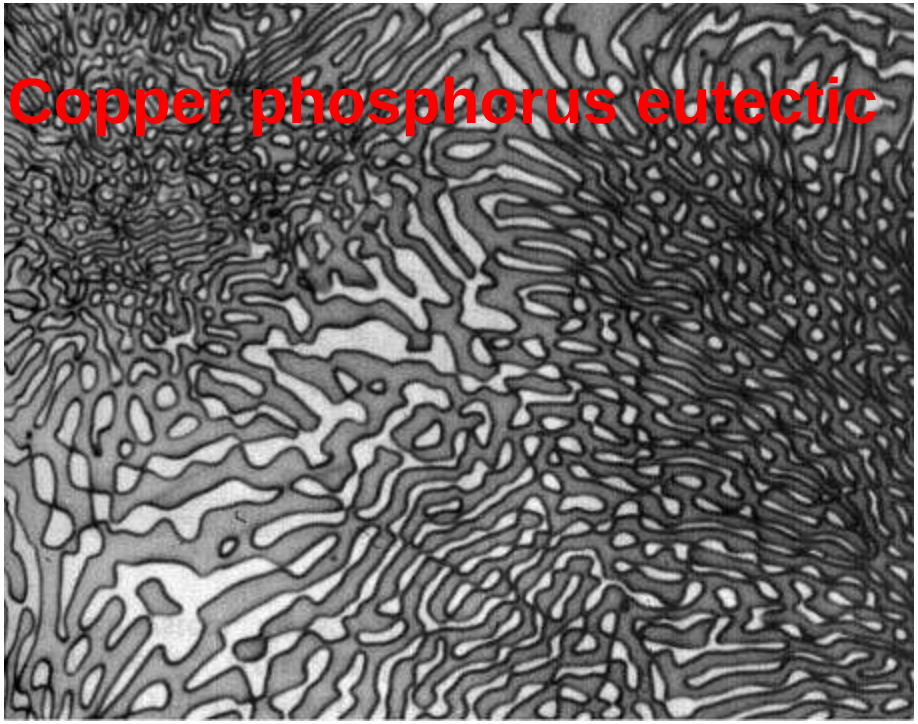
The dark layers are Pb-rich α phase, the light layers are the Sn-rich β phase.

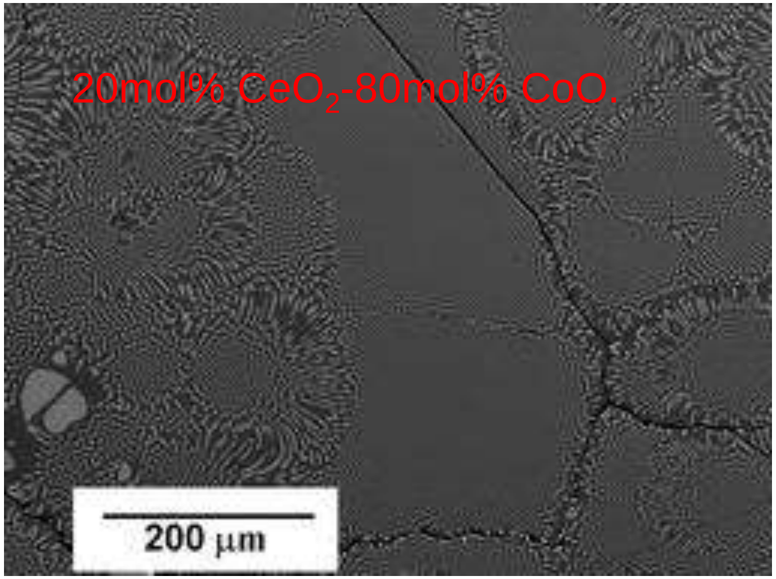





Ni-Al


Ir-Si

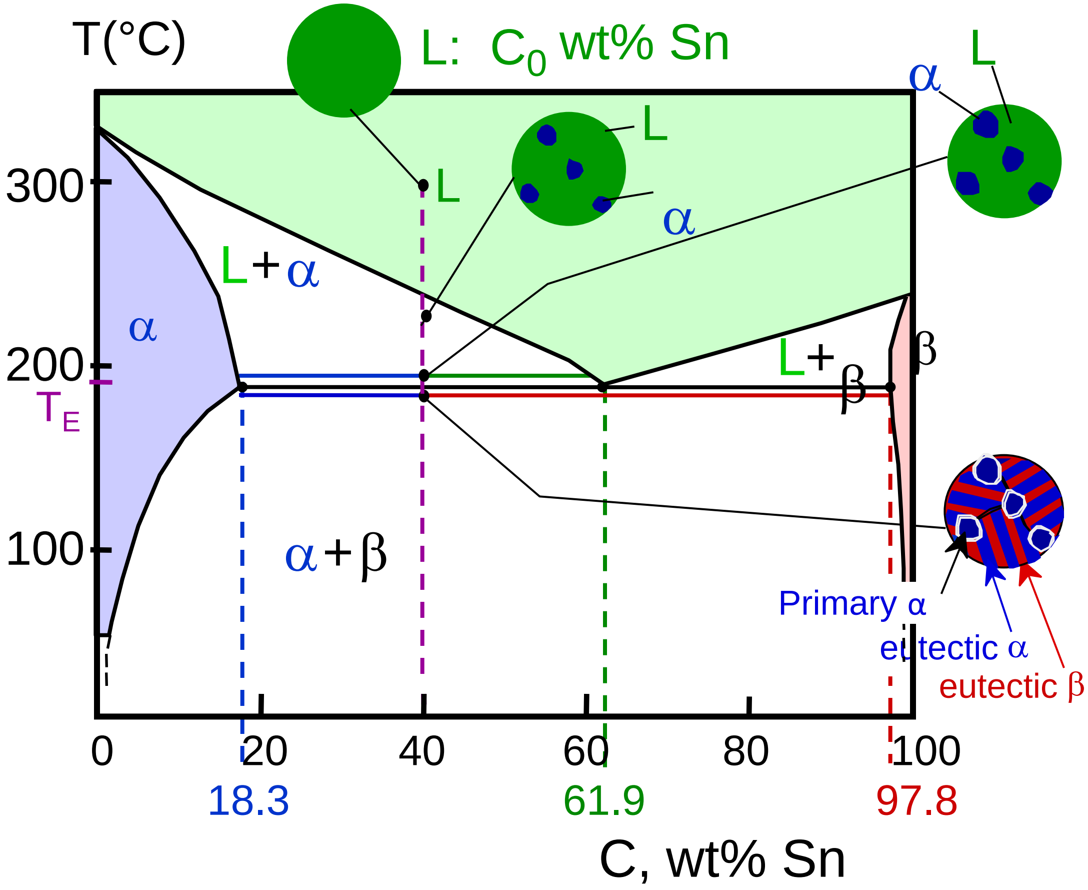

Copper phosphorus eutectic


20mol% CeO_2-80mol% CoO.

Microstructures in Eutectic Systems - IV

Pb-Sn system

- For alloys with18.3 wt% Sn < C_0 < 61.9 wt% Sn
- Result: α phase particles and a eutectic microconstituent



- Just above T_E :

C_α = 18.3 wt% Sn

C_L = 61.9 wt% Sn

$$W_\alpha = \frac{C_L - C_0}{C_L - C_\alpha} = 0.50$$

$W_L = (1- W_\alpha) = 0.50$

- Just below T_E :

C_α = 18.3 wt% Sn

C_β = 97.8 wt% Sn

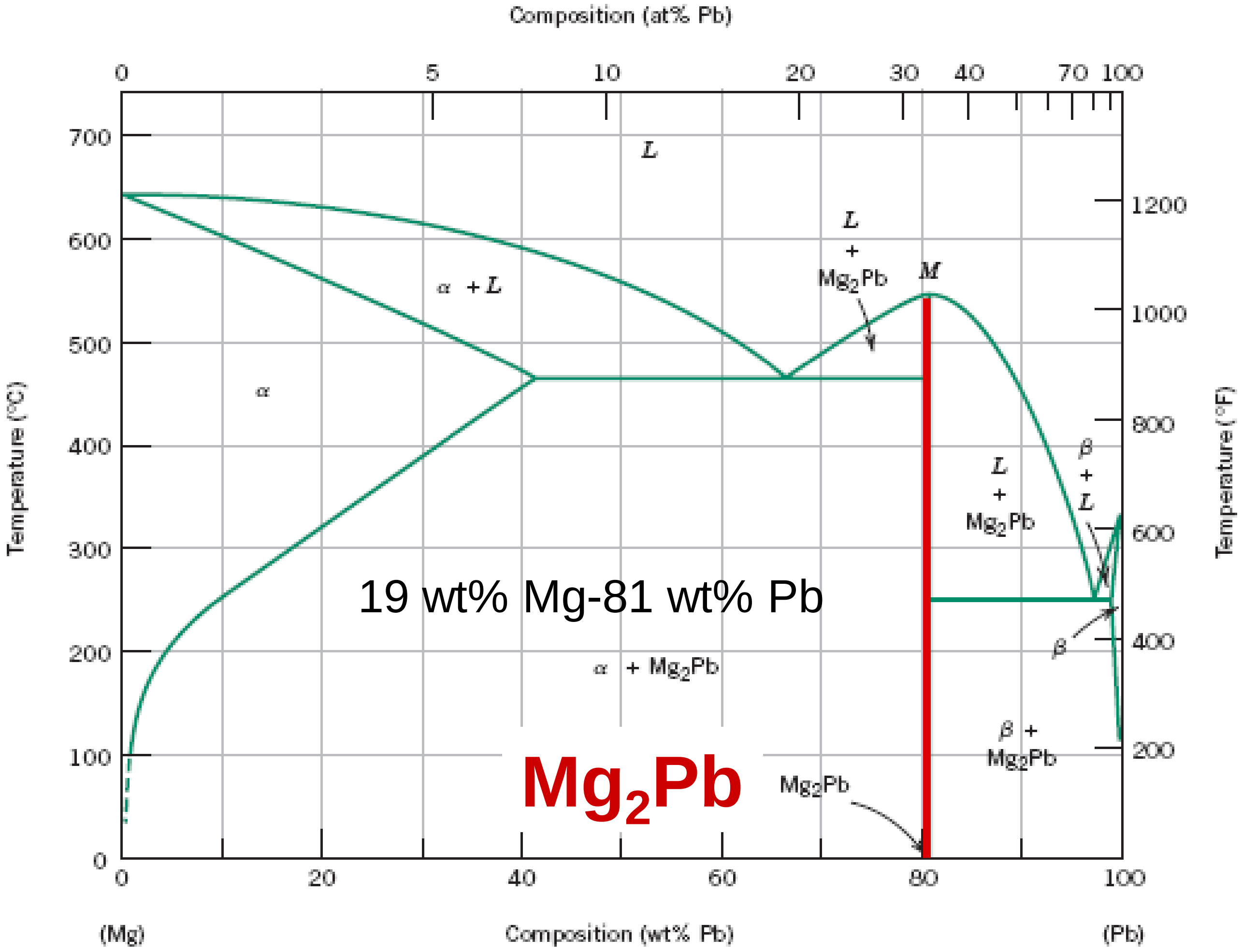
$$W_\alpha = \frac{C_\beta - C_0}{C_\beta - C_\alpha} = 0.727$$

W_β = 0.273 wt% Sn

Chapter 10 (part 2)

- Equilibrium Diagrams with Intermediate Phases or Compounds
- Eutectoid and Peritectic Reactions
- Ceramic Phase Diagrams
- The Gibbs Phase Rule
- The Iron-Iron Carbide Phase Diagram
- Development of Microstructures in Iron-Carbon Alloys
- Hypoeutectoid Alloys
- Hypereutectoid Alloys
- Influence of Other Alloying Elements

Intermetallic Compounds

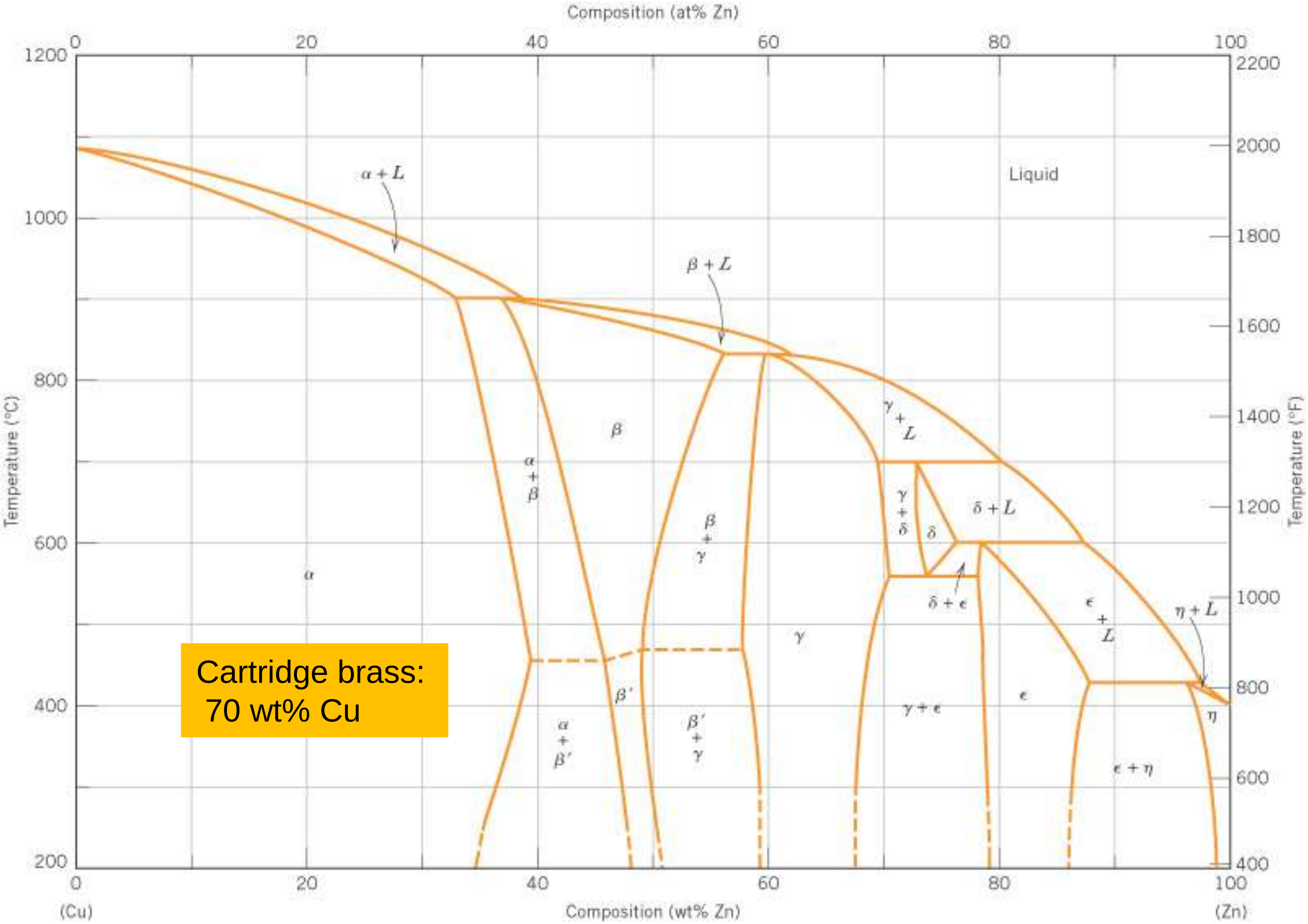


19 wt% Mg-81 wt% Pb

Mg_2Pb

Note: intermetallic compounds exist as a line on the diagram - not a phase region. The composition of a compound has a distinct chemical formula.

Cu-Zn System (Brass)

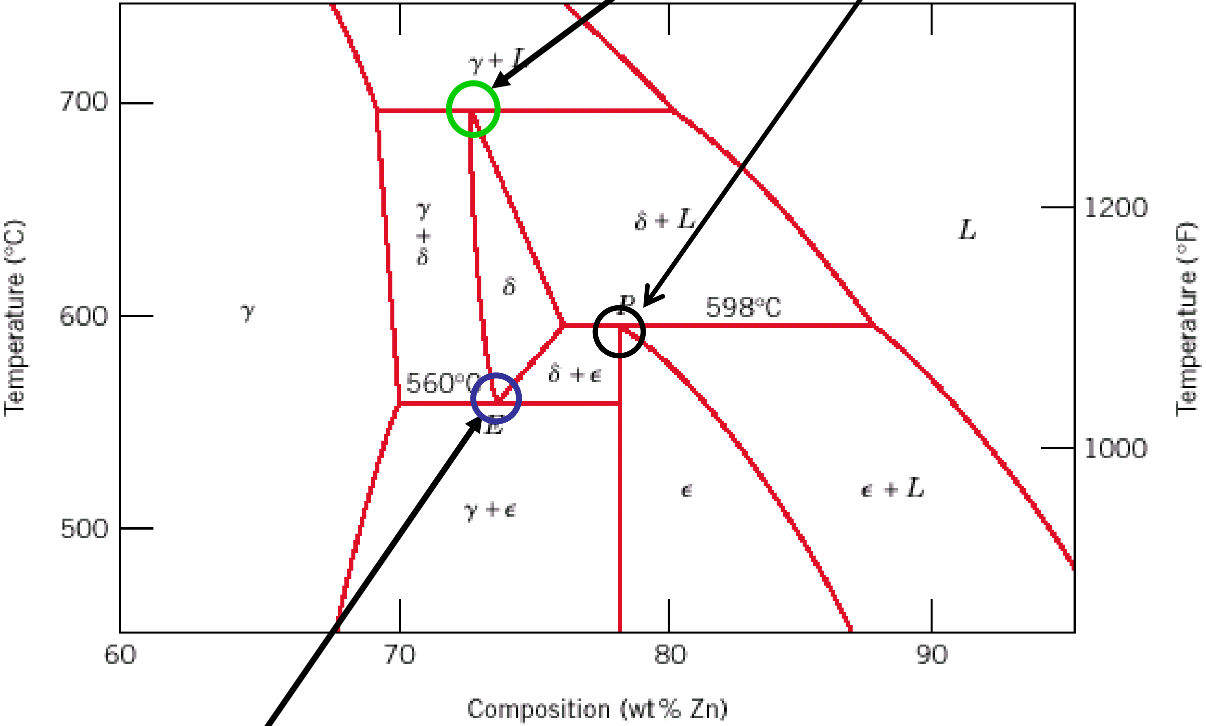


Cartridge brass:
70 wt% Cu

Eutectoid & Peritectic

Peritectic transformation $\gamma + L \rightleftharpoons \delta$

Cu-Zn Phase diagram



Eutectoid transformation $\delta \rightleftharpoons \gamma + \varepsilon$

Eutectic, Eutectoid, & Peritectic

- Eutectic - liquid transforms to two solid phases

  $L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + \beta$ (For Pb-Sn, 183°C, 61.9 wt% Sn)

- Eutectoid – one solid phase transforms to two other solid phases

  $\text{Solid}_1 \leftrightarrow \text{Solid}_2 + \text{Solid}_3$

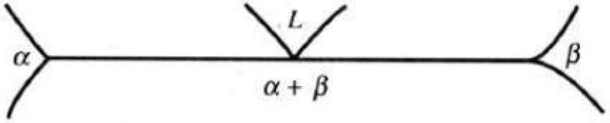
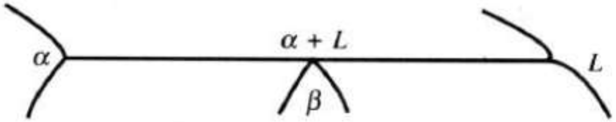
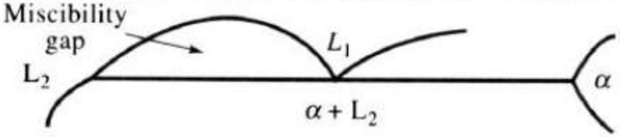
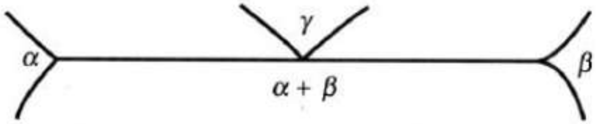
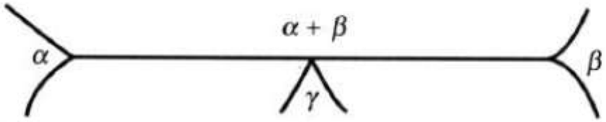
  $\gamma \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + Fe_3C$ (For Fe-C, 727°C, 0.76 wt% C)

- Peritectic - liquid and one solid phase transform to a 2nd solid phase

  $\text{Solid}_1 + \text{Liquid} \leftrightarrow \text{Solid}_2$

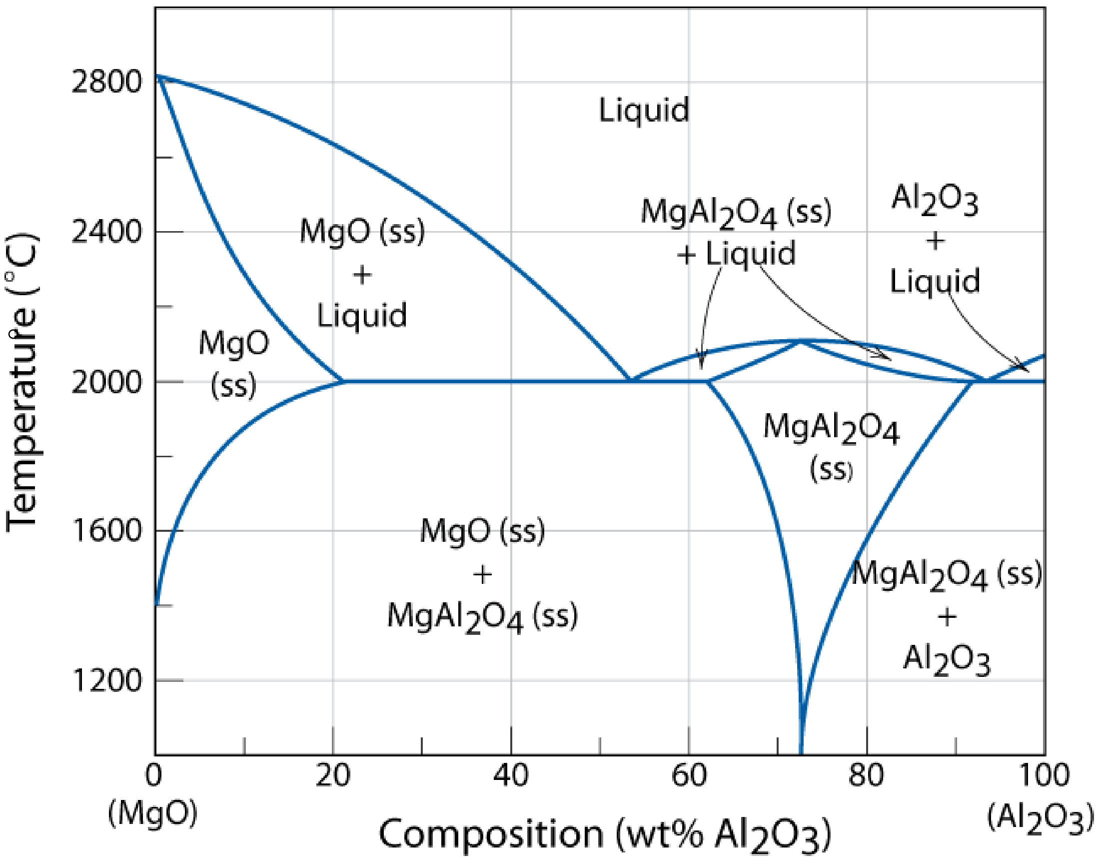
  $\delta + L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \varepsilon$ (For Cu-Zn, 598°C, 78.6 wt% Zn)

Three-Phase Reactions

Eutectic	$L \rightarrow \alpha + \beta$	
Peritectic	$\alpha + L \rightarrow \beta$	
Monotectic	$L_1 \rightarrow L_2 + \alpha$	
Eutectoid	$\gamma \rightarrow \alpha + \beta$	
Peritectoid	$\alpha + \beta \rightarrow \gamma$	

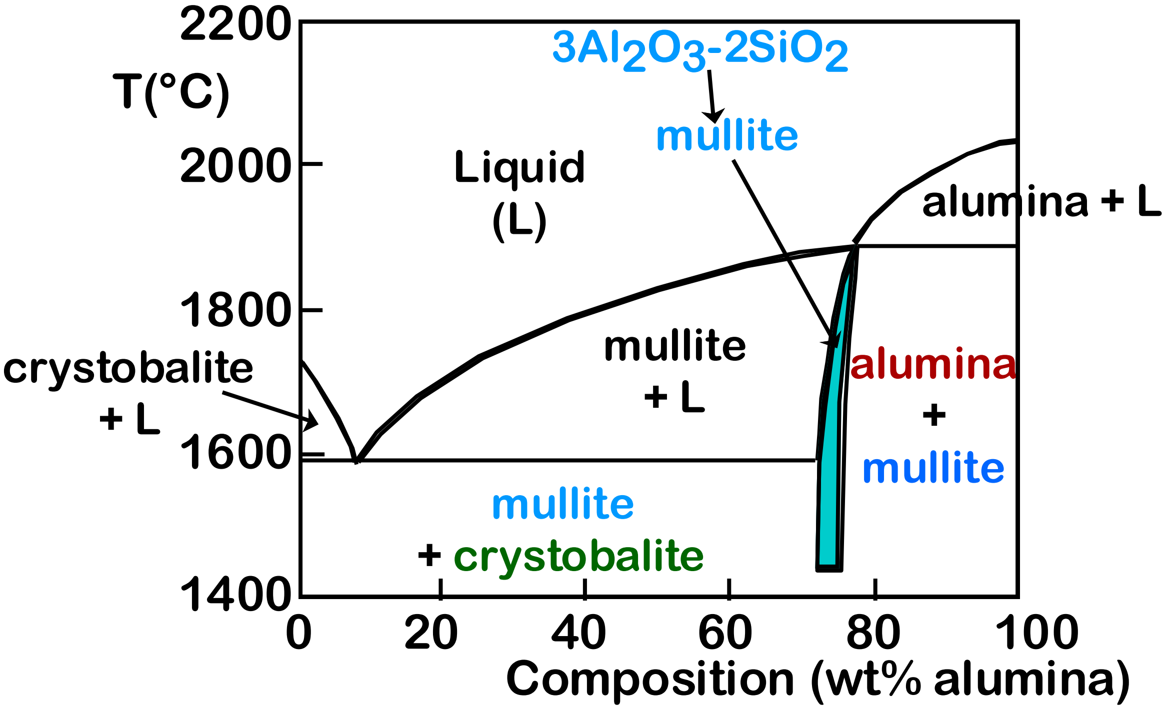
Ceramic Phase Diagrams

MgO-Al_2O_3 diagram:

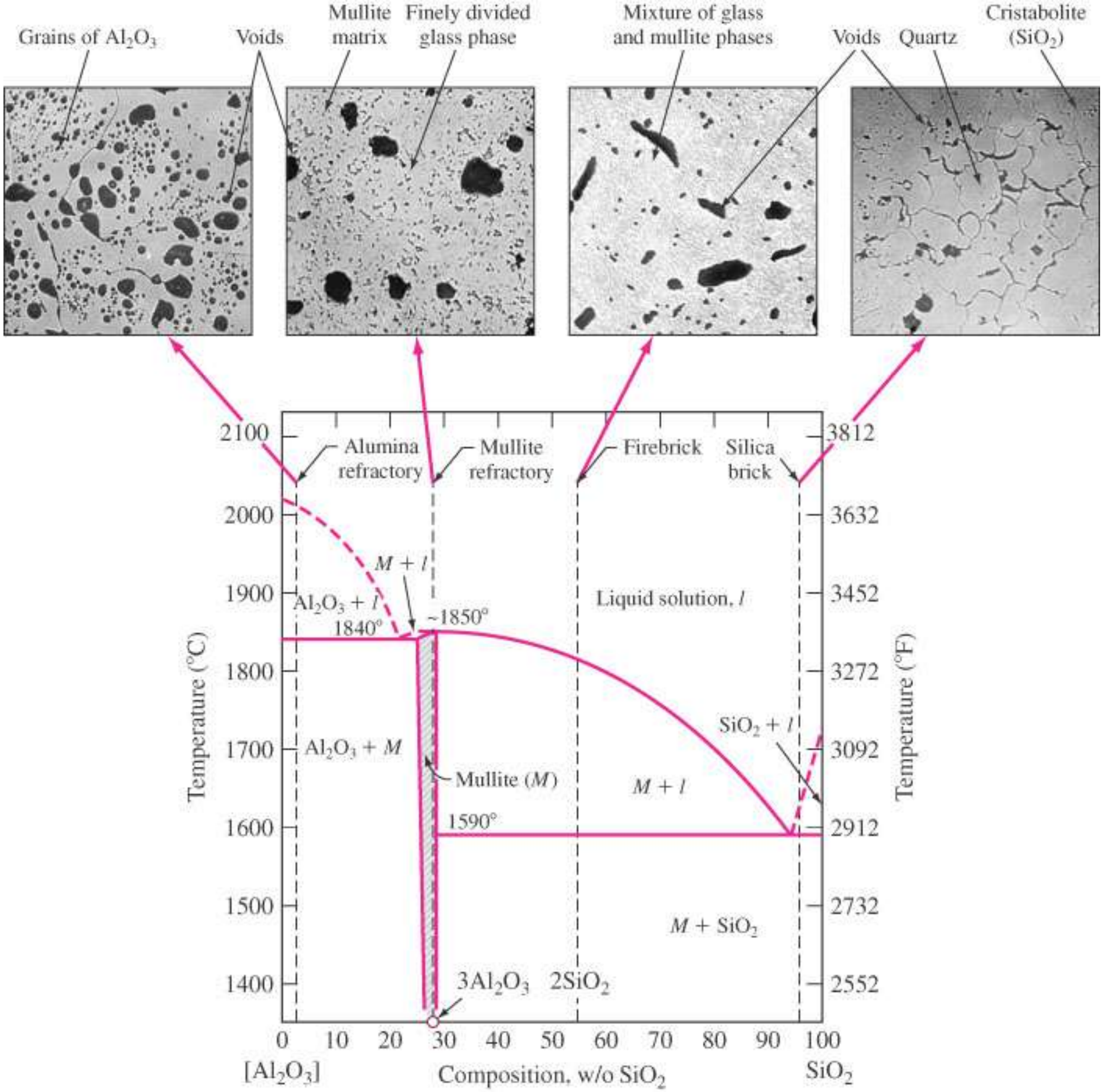


APPLICATION: REFRACTORIES

- Need a material to use in high temperature furnaces.
- Consider Silica (SiO_2) - Alumina (Al_2O_3) system.
- Phase diagram shows: mullite, alumina and crystobalite (made up of SiO_2) are candidate refractories.



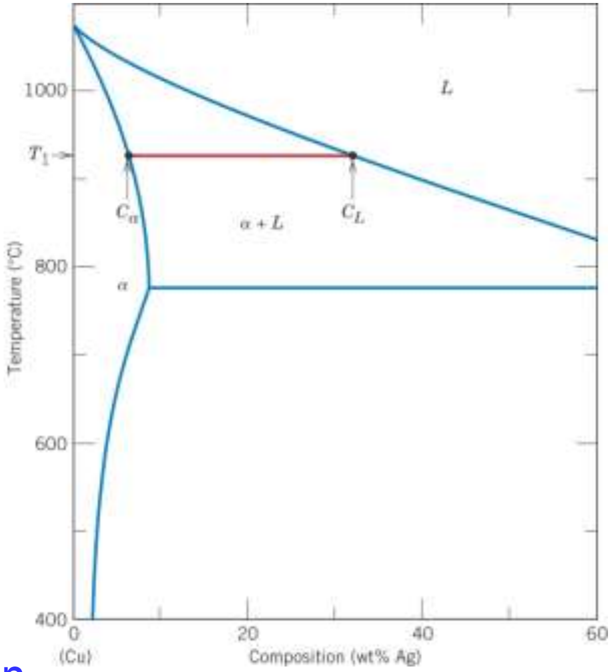
Ceramic Phases and Cements



Gibbs Phase Rule

- Phase diagrams and phase equilibria are subject to the laws of thermodynamics.
- Gibbs phase rule is a criterion that determines how many phases can coexist within a system at equilibrium.

$$P + F = C + N$$



P: # of phases present

F: degrees of freedom (temperature, pressure, composition)

C: components or compounds

N: noncompositional variables

For the Cu-Ag system @ 1 atm for a single phase P:

N=1 (temperature), C = 2 (Cu-Ag), P= 1 (α, β, L)

$F = 2 + 1 - 1 = 2$

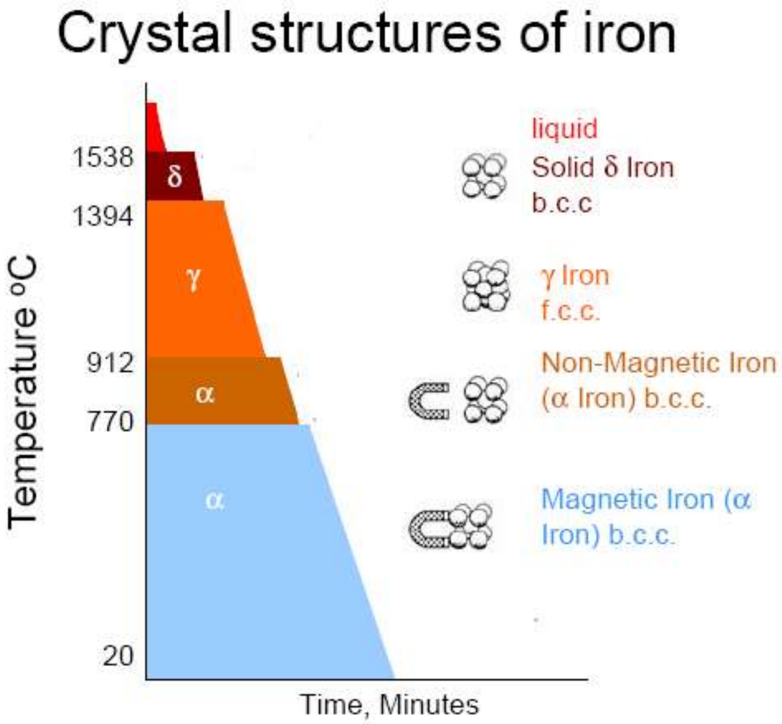
This means that to characterize the alloy within a single phase field, 2 parameters must be given: temperature and composition.

If 2 phases coexist, for example, α+L , β+L, $\alpha+\beta$, then according to GPR, we have 1 degree of freedom: $F = 2 + 1 - 2 = 1$. So, if we have Temp or composition, then we can completely define the system.

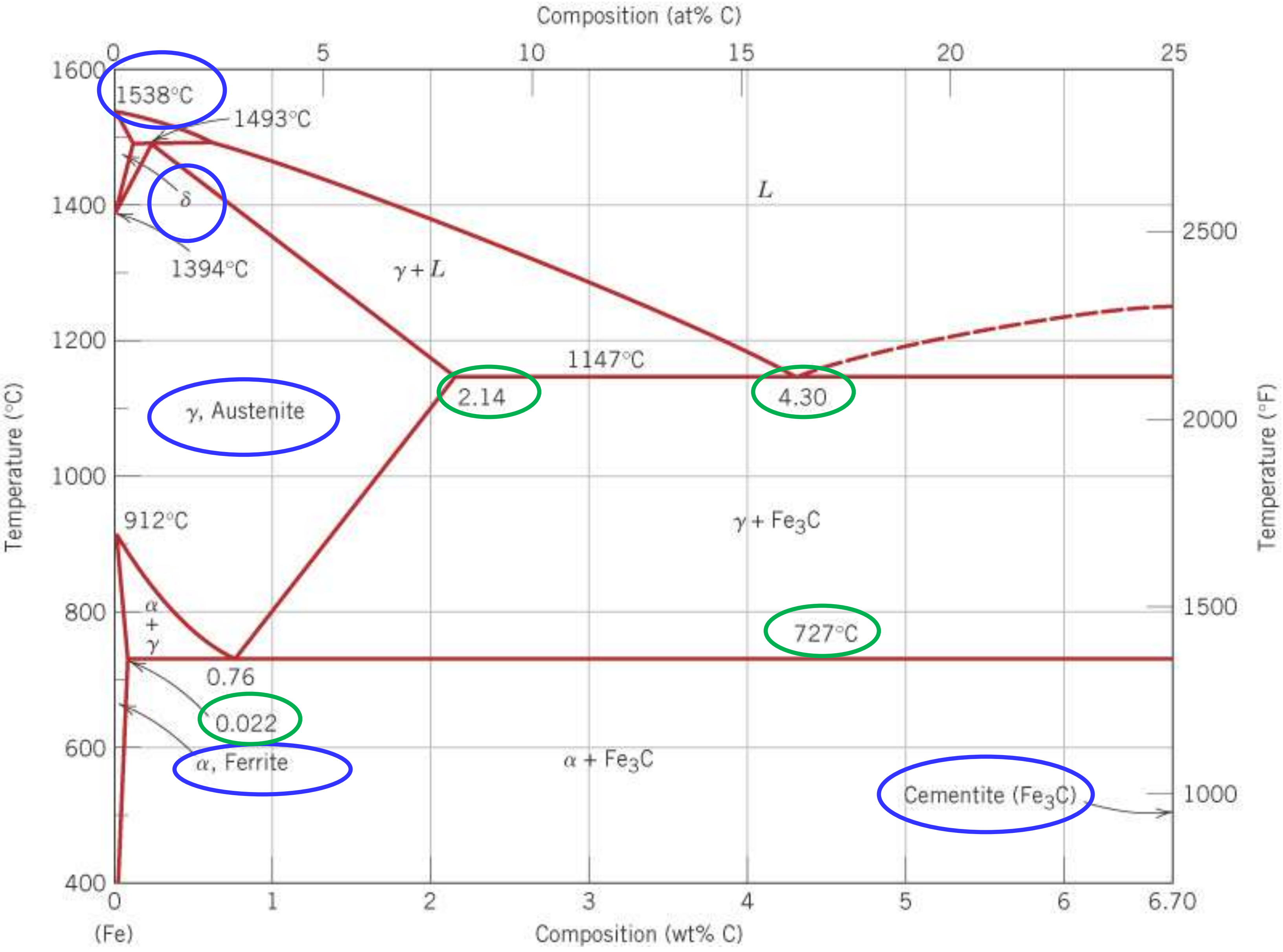
If 3 phases exist (for a binary system), there are 0 degrees of freedom. This means the composition and Temp are fixed. This condition is met for a eutectic system by the eutectic isotherm.

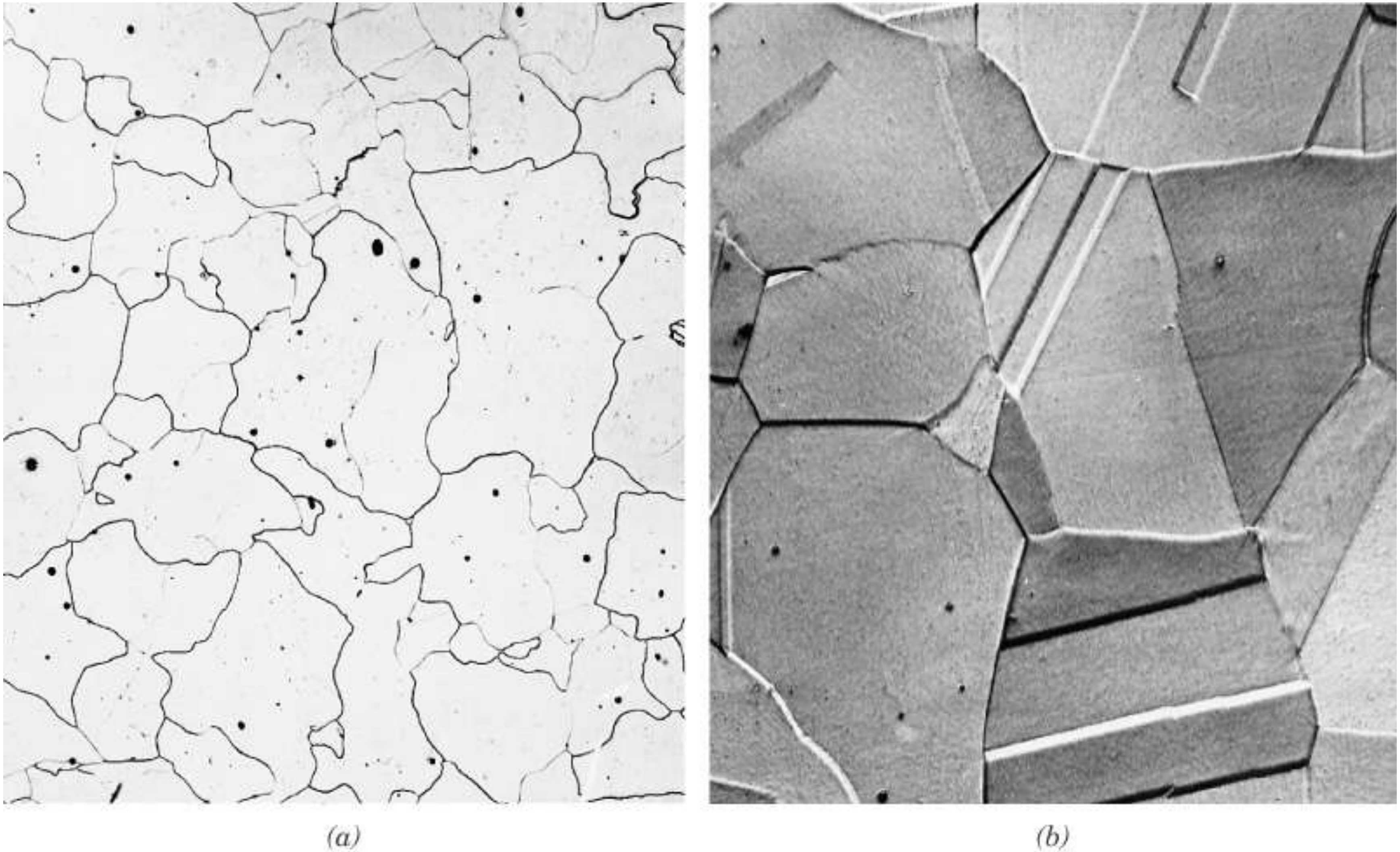
Iron-Carbon System

- Pure iron when heated experiences 2 changes in crystal structure before it melts.
- At room temperature the stable form, ferrite (α iron) has a BCC crystal structure.
- Ferrite experiences a polymorphic transformation to FCC austenite (γ iron) at 912 ˚C (1674 ˚F).
- At 1394˚C (2541˚F) austenite reverts back to BCC phase δ ferrite and melts at 1538 ˚C (2800 ˚F).
- Iron carbide (cementite or Fe_3C) an intermediate compound is formed at 6.7 wt% C.
- Typically, all steels and cast irons have carbon contents less than 6.7 wt% C.
- Carbon is an interstitial impurity in iron and forms a solid solution with the α, γ, δ phases.



Iron-Carbon System





(a) (b)

Though carbon is present in relatively low concentrations, it significantly influences the mechanical properties of ferrite: (a) α ferrite, (b) austenite.

4 Solid Phases

- **α-ferrite**
  - solid solution of carbon in a iron,
  - BCC structure
  - carbon only slightly soluble in the matrix
    - maximum solubility of 0.02%C at 723°C to about 0.008%C at room temperature.
- **Austenite (γ)**
  - solid solution of carbon in γ–iron
  - FCC structure: can accommodate more carbon than ferrite
    - maximum of 2.08%C at 1148°C, decreases to 0.8%C at 723°C
    - difference in C solid solubility between γ and α is the basis for **hardening** of most steels.

δ-ferrite
  - solid solution of carbon in δ–iron
  - BCC crystal structure
    - maximum solubility of ferrite being 0.09%C at 1495°C

- **Cementite (Fe_3C)**
  - intermetallic Fe-C compound
    - Fe_3C : 6.67%C and 93.3%Fe.
  - orthorhombic crystal structure: hard and brittle

Iron carbide (Cementite or Fe_3C)

- Forms when the solubility limit of carbon in α ferrite is exceeded at temperatures below 727 °C.
- Mechanically, cementite is very hard and brittle.
- For ferrous alloys there are 3 basic types, based on carbon content:
  - ☐ Iron (ferrite phase): <0.008 wt% C room temp
  - ☐ Steel (α + Fe_3C phase): 0.008 to 2.14 wt% C
  - ☐ Cast iron: 2.14 to 6.70 wt% C

Iron-Carbon (Fe-C) Phase Diagram

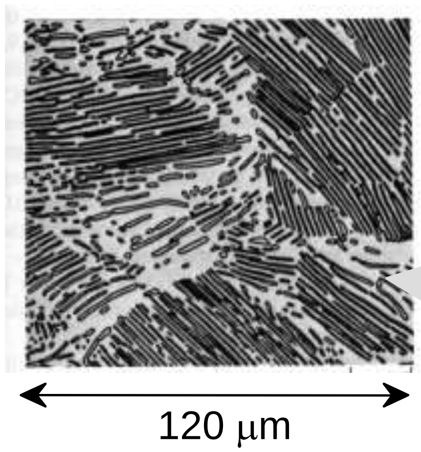
- 2 important points

  - **Eutectic (A):**

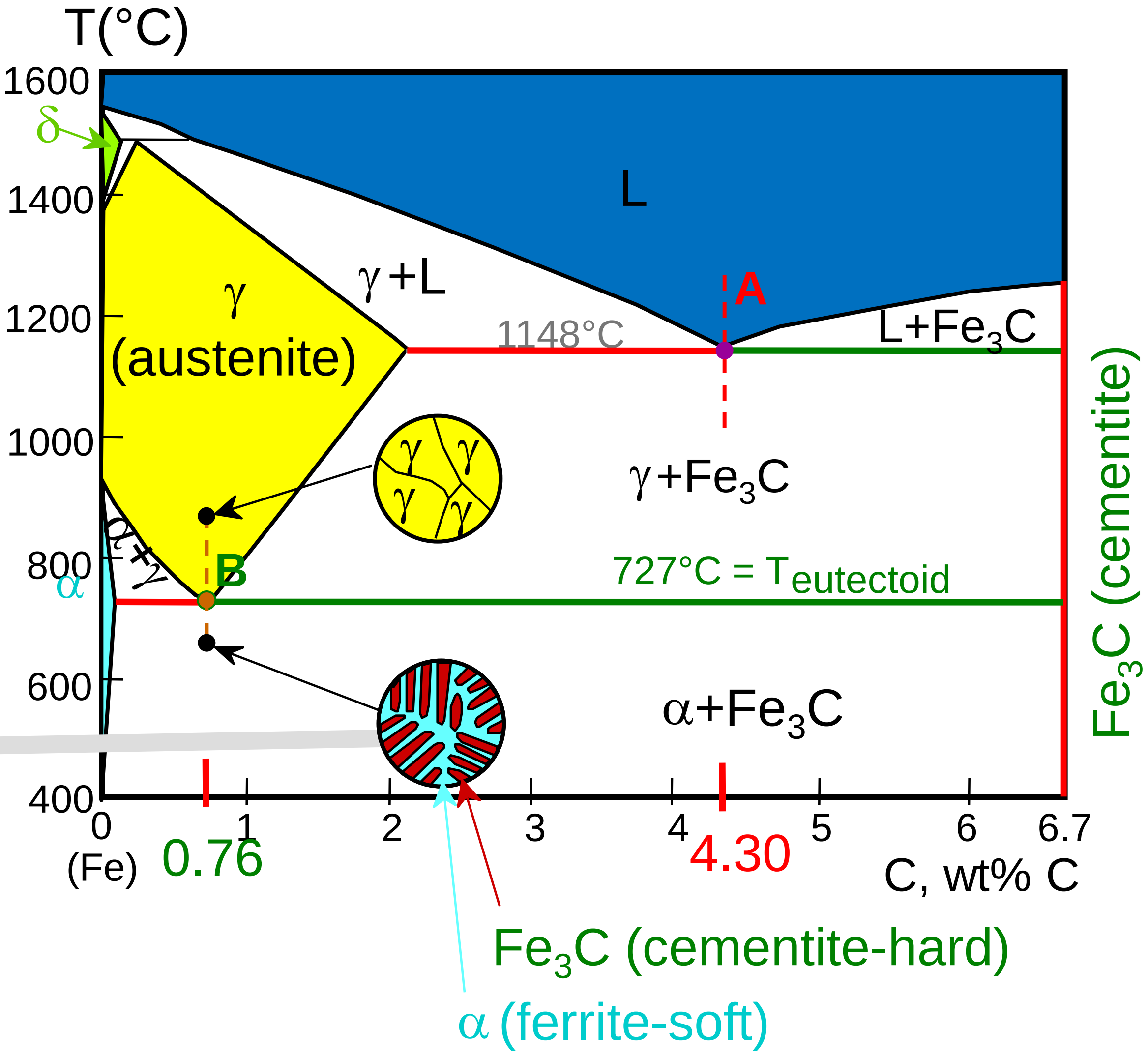
$$L \leftrightarrow \gamma + Fe_3C$$

  - **Eutectoid (B):**

$$\gamma \leftrightarrow \alpha + Fe_3C$$



Result: Pearlite = alternating layers of α and Fe_3C phases, not a separate phase.

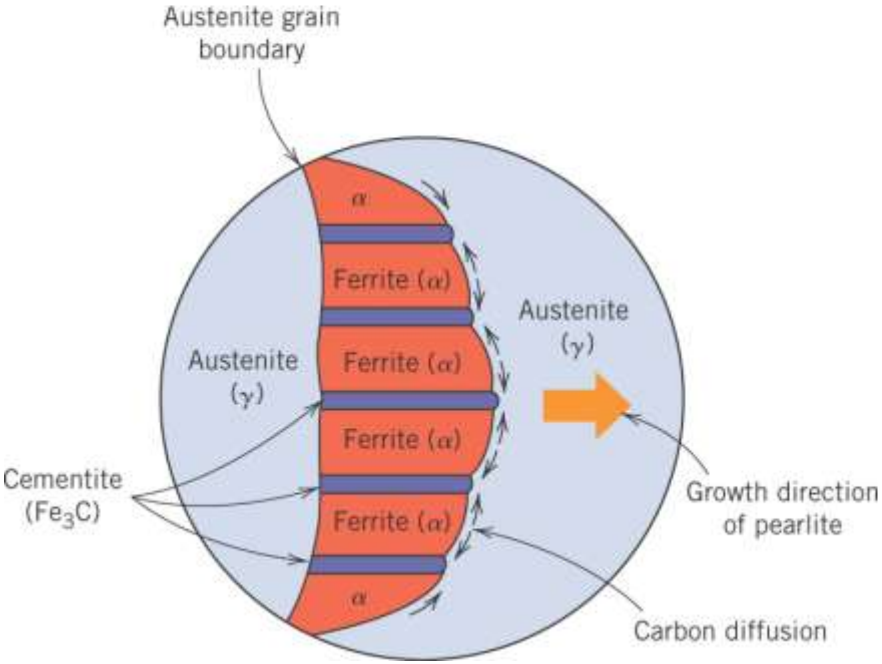


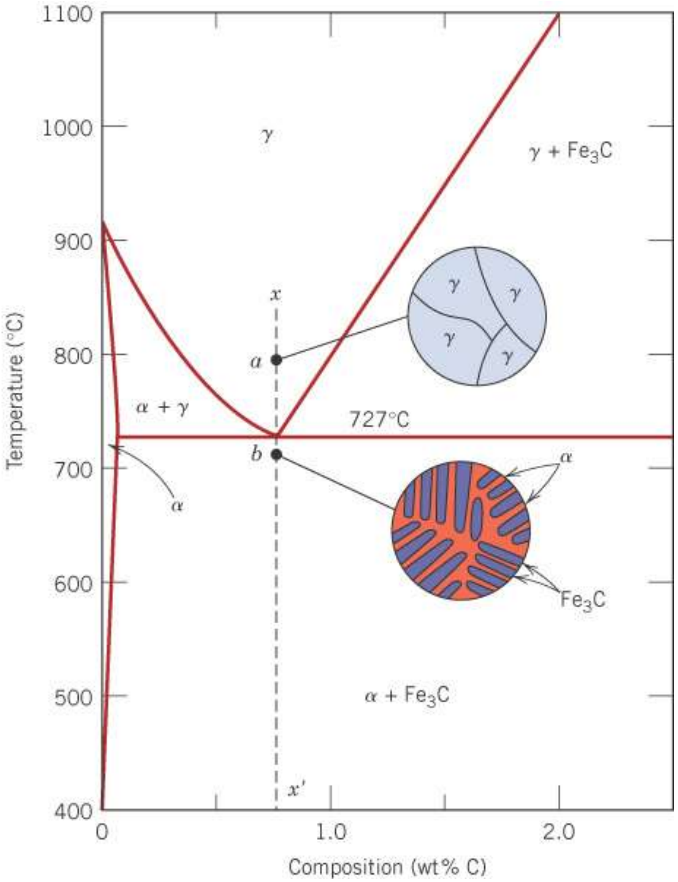
Eutectoid reaction:

Pearlite

$$\gamma \leftrightarrow \alpha + Fe_3C$$

- formation of the pearlite structure
  - nucleating at γ grain boundaries
  - growth by diffusion of C to achieve the compositions of α and Fe_3C (with structural changes)
  - α lamellae much thicker





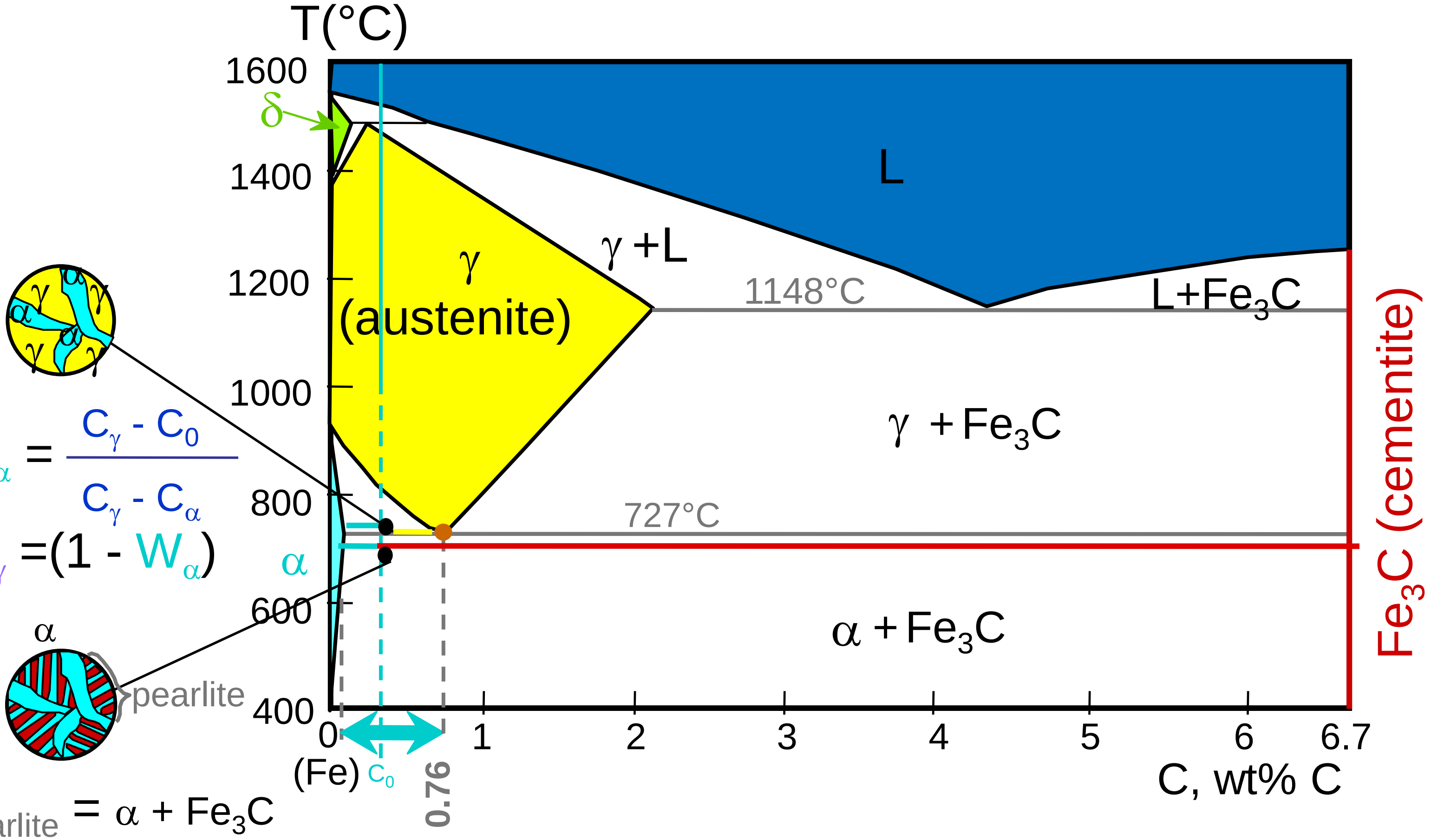
Redistribution of carbon by diffusion

Austenite – 0.76 wt% C

Ferrite - 0.022 wt% C

Cementite - 6.70 wt% C

Hypoeutectoid Steel



$$W_\alpha = \frac{C_\gamma - C_0}{C_\gamma - C_\alpha}$$

$$W_\gamma = (1 - W_\alpha)$$

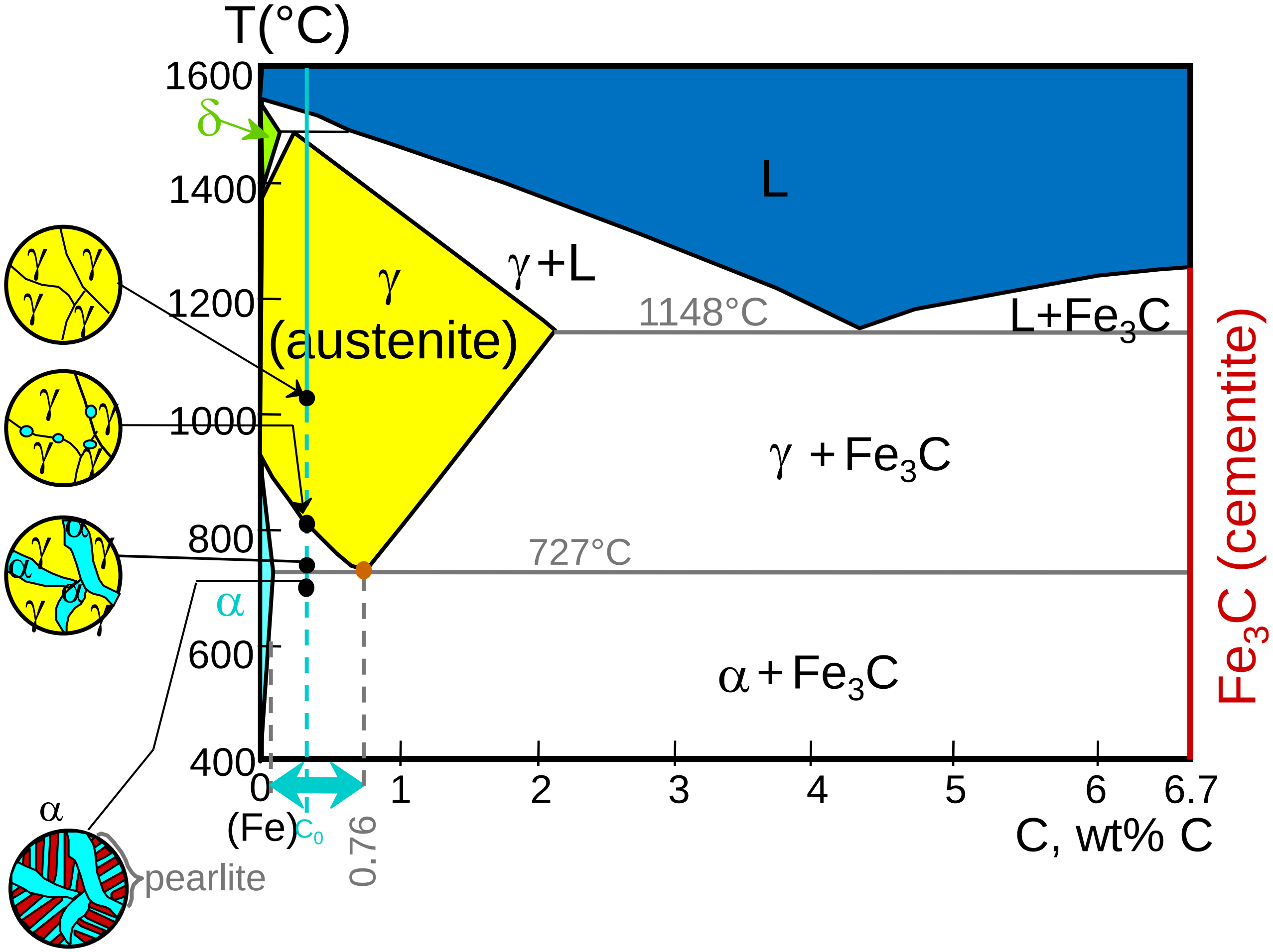
pearlite = α + Fe$_3$C

$$W_{\alpha'} = \frac{C_{Fe3C} - C_0}{C_{Fe3C} - C_\alpha}$$

$$W_{pearlite} = (1 - W_{\alpha'})$$

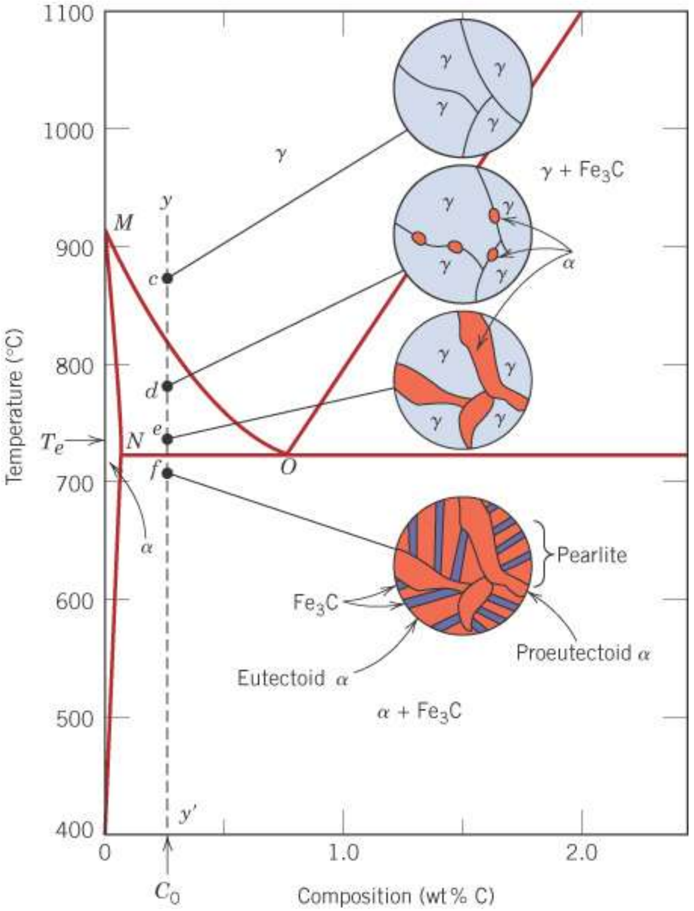
Microstructures for iron-iron carbide alloys that are below the eutectoid with compositions between 0.022 and 0.76 wt% Carbon are hypoeutectoid.

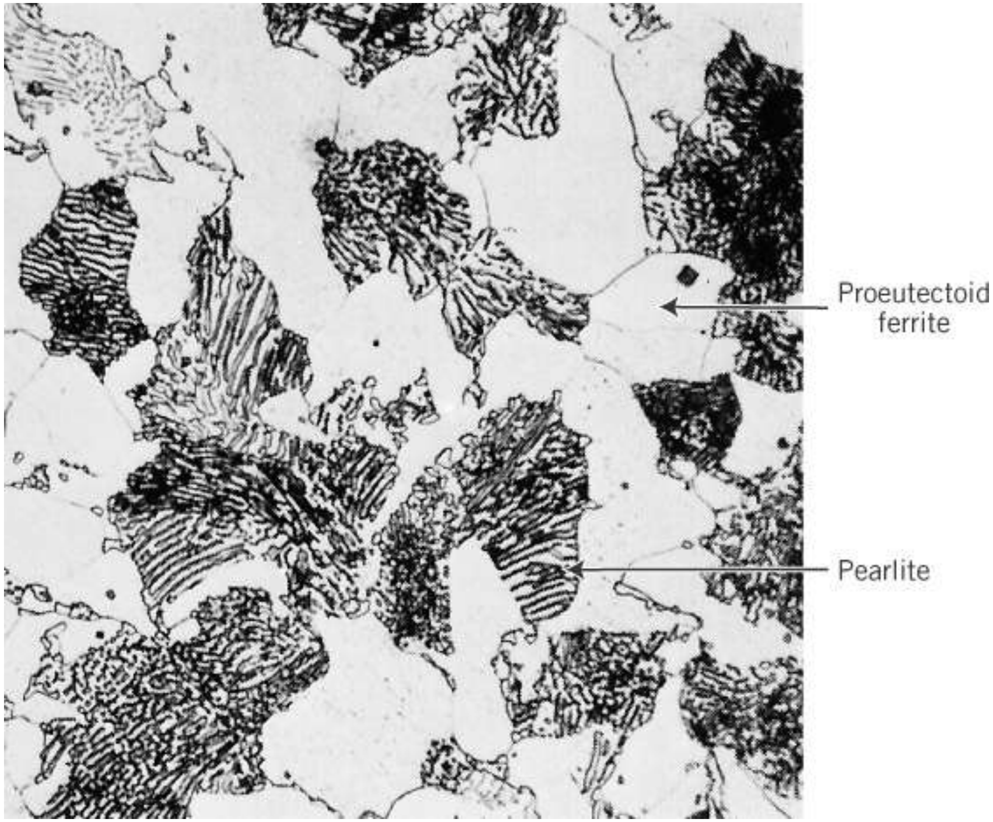
Hypoeutectoid Steel



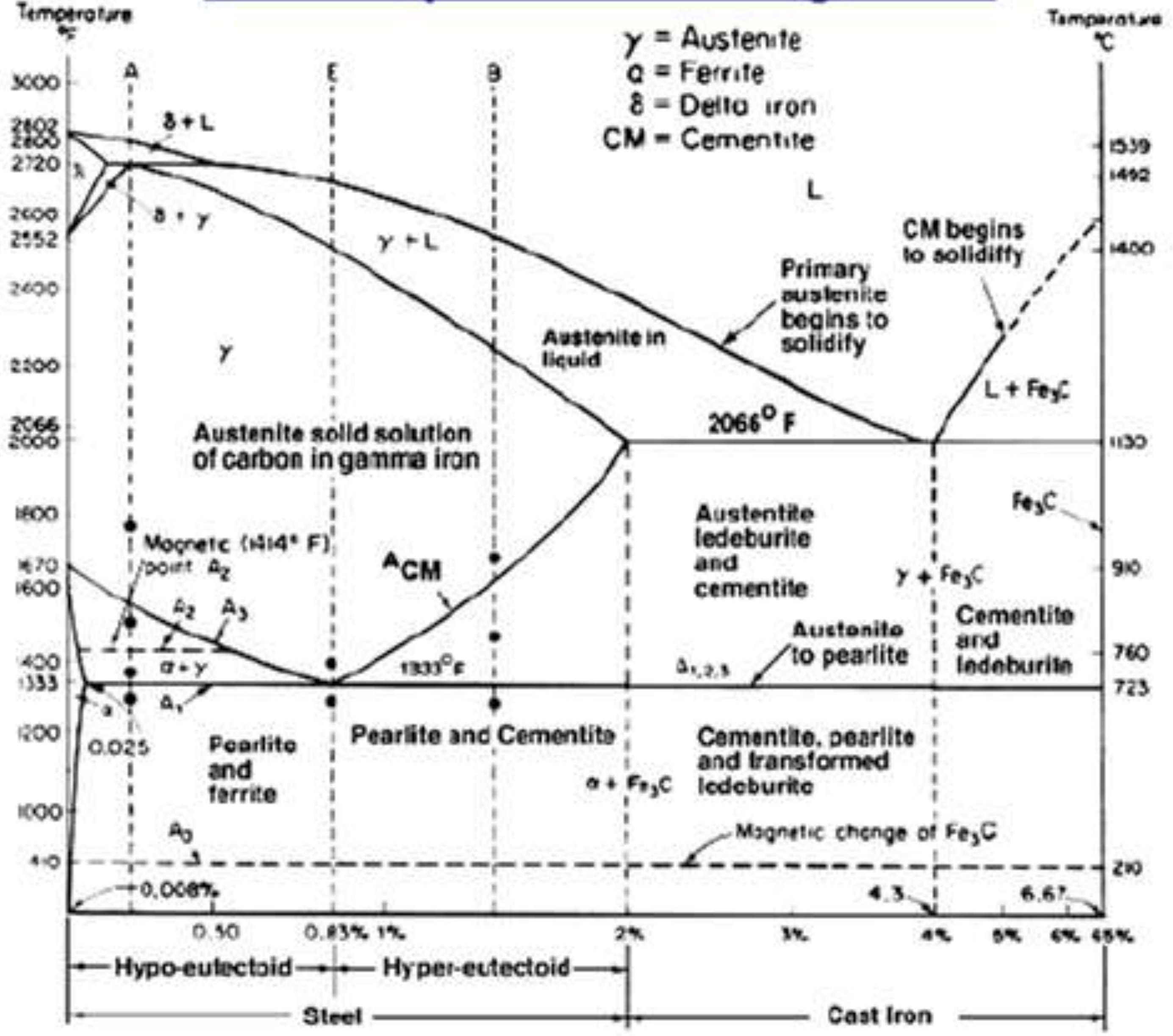
Proeutectoid

- Formed before the eutectoid
- Ferrite that is present in the pearlite is called eutectoid ferrite.
- The ferrite that is formed above the $T_{\text{eutectoid}}$ (727°C) is proeutectoid.

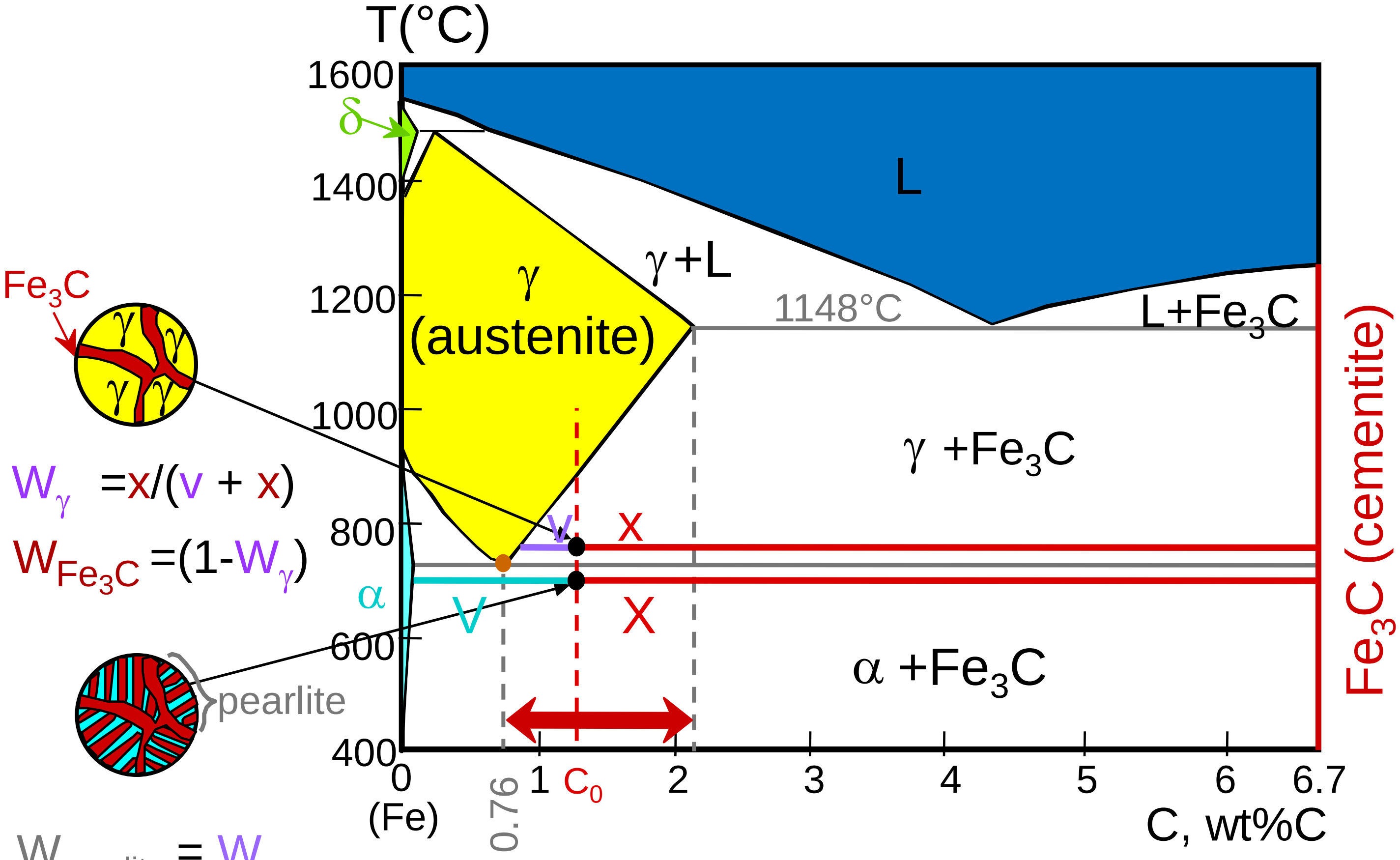




Fe-C phase diagram



Hypereutectoid Steel



$W_\gamma = x/(v + x)$

$W_{Fe_3C} = (1 - W_\gamma)$

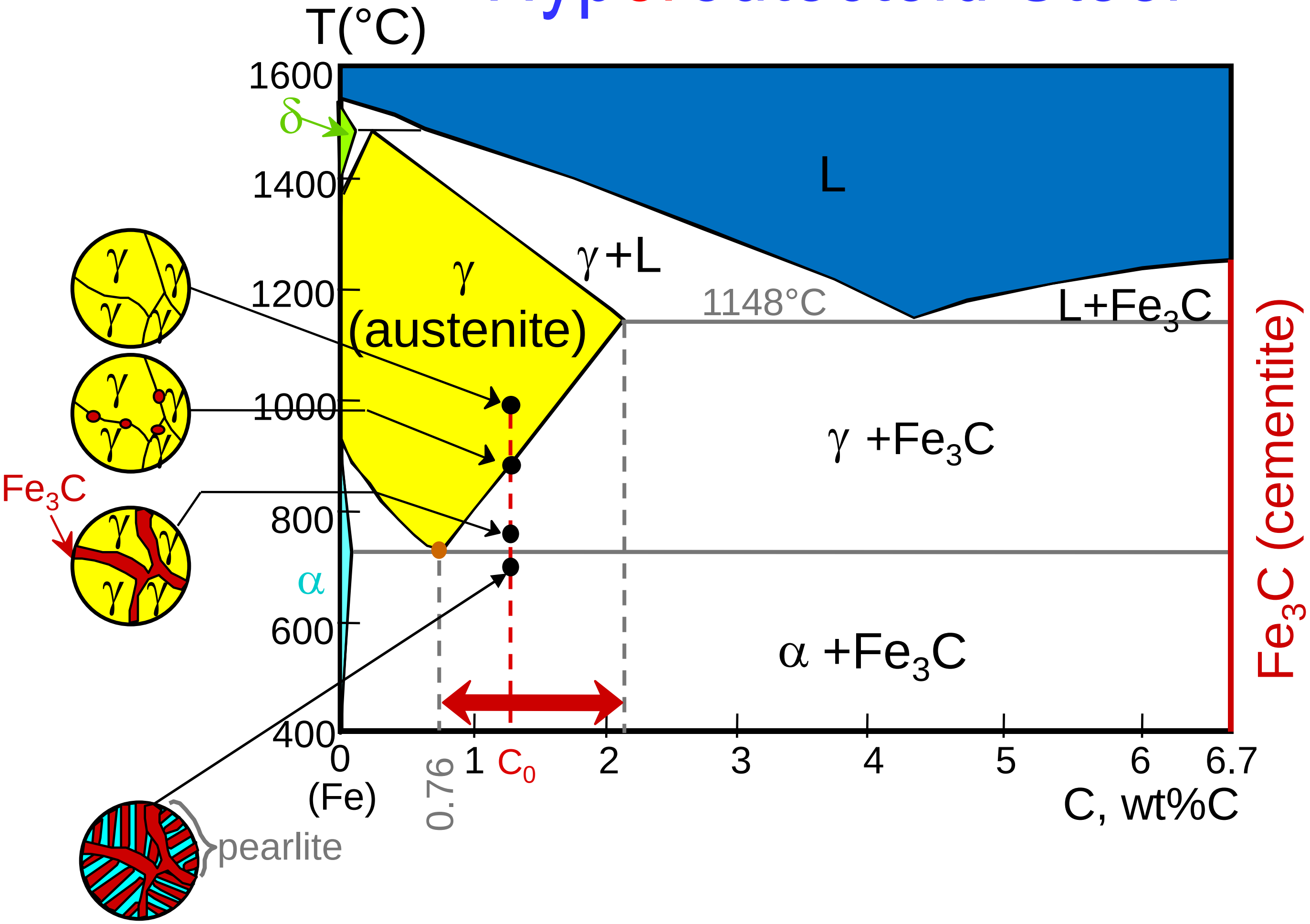
$W_{pearlite} = W_\gamma$

$W_\alpha = X/(V + X)$

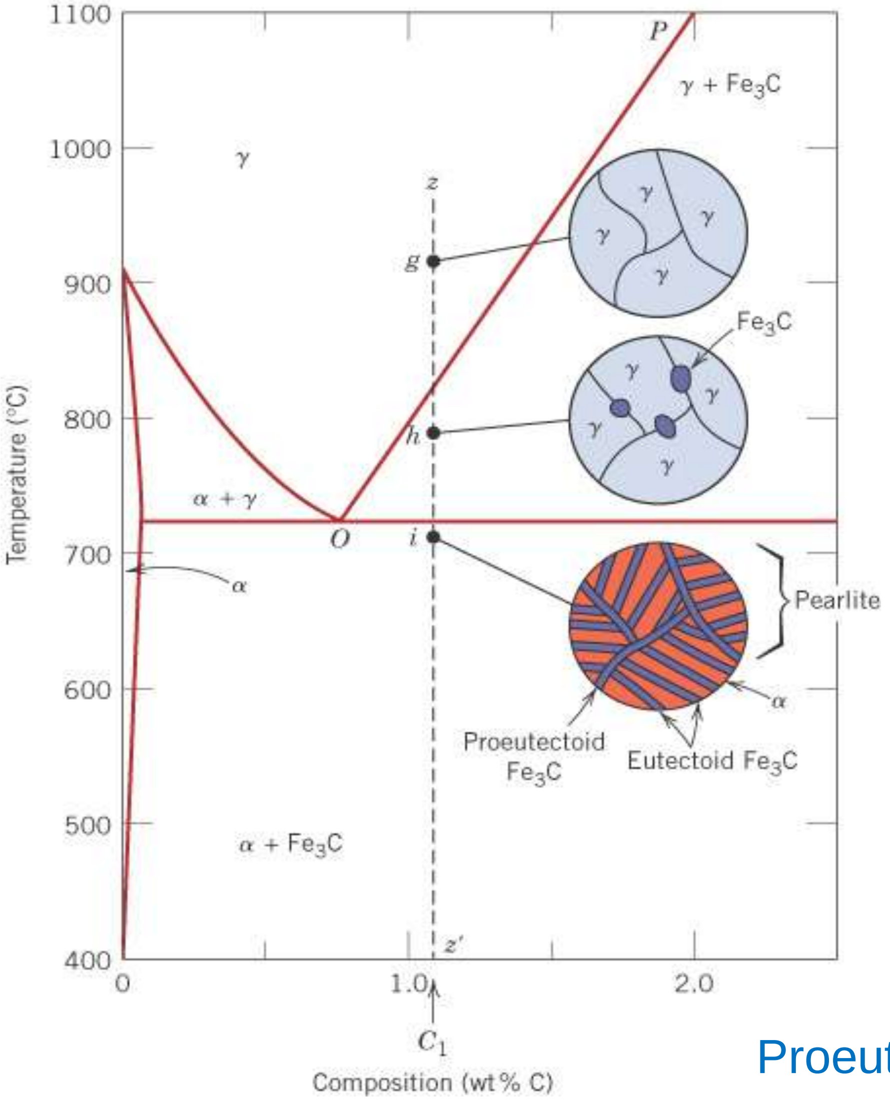
$W_{Fe_3C'} = (1 - W_\alpha)$

Microstructures for iron-iron carbide alloys that have compositions between 0.76 and 2.14 wt% carbon are hypereutectoid (more than eutectoid).

Hypereutectoid Steel

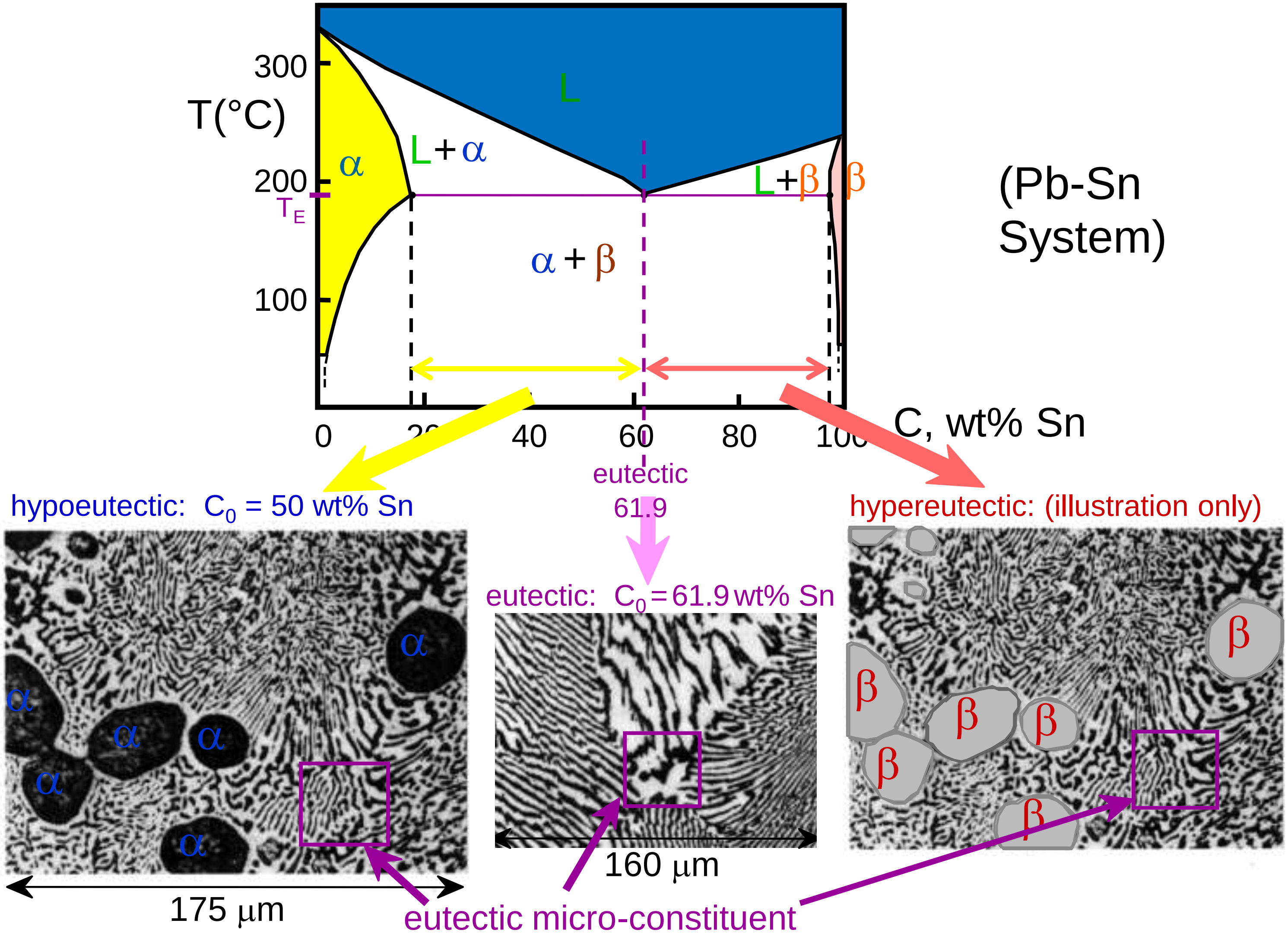


Hypereutectoid Steel (1.2 wt% C)

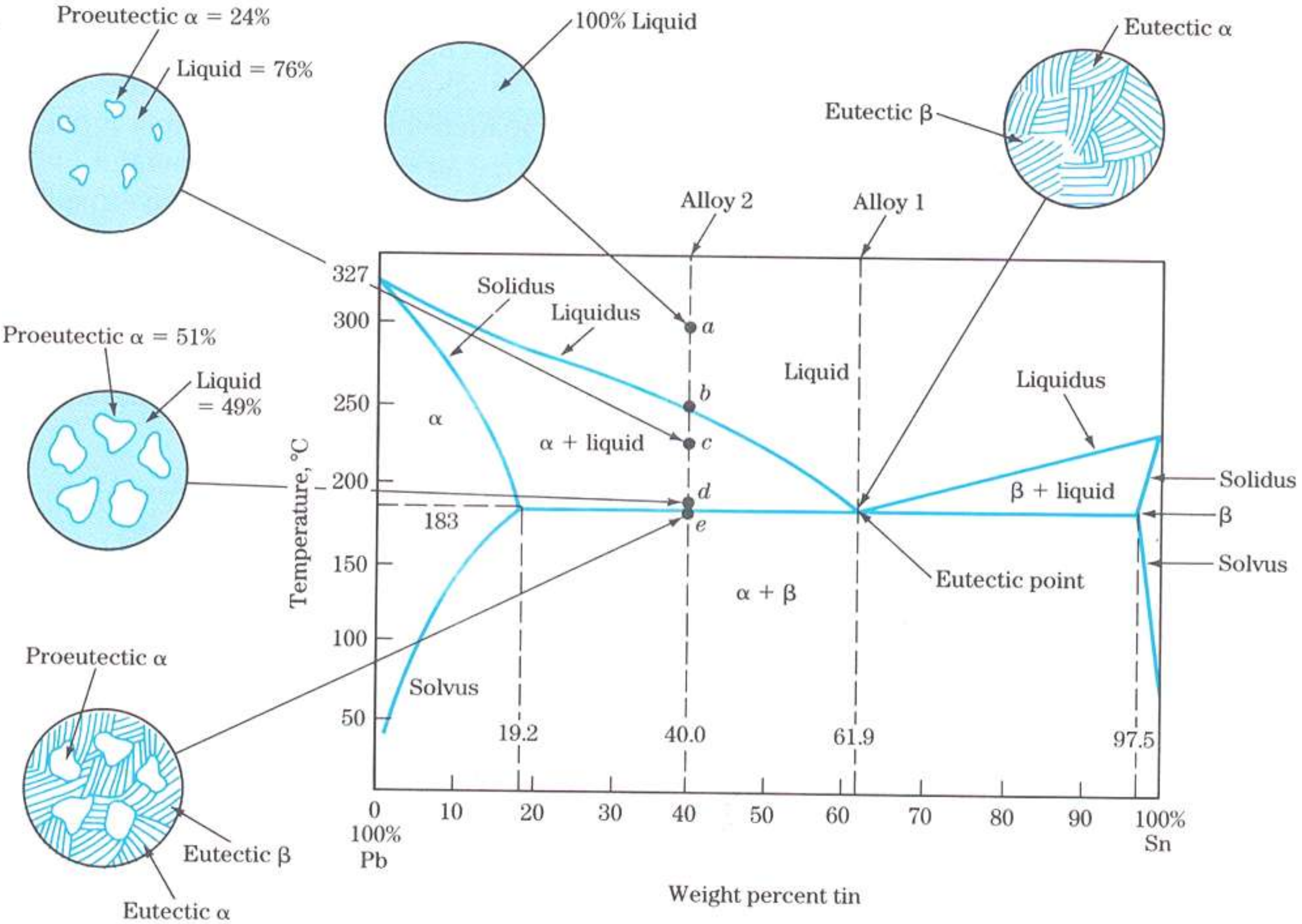


Proeutectoid: formed above the $T_{eutectoid}$ (727°C)

Hypoeutectic & Hypereutectic



(Pb-Sn System)

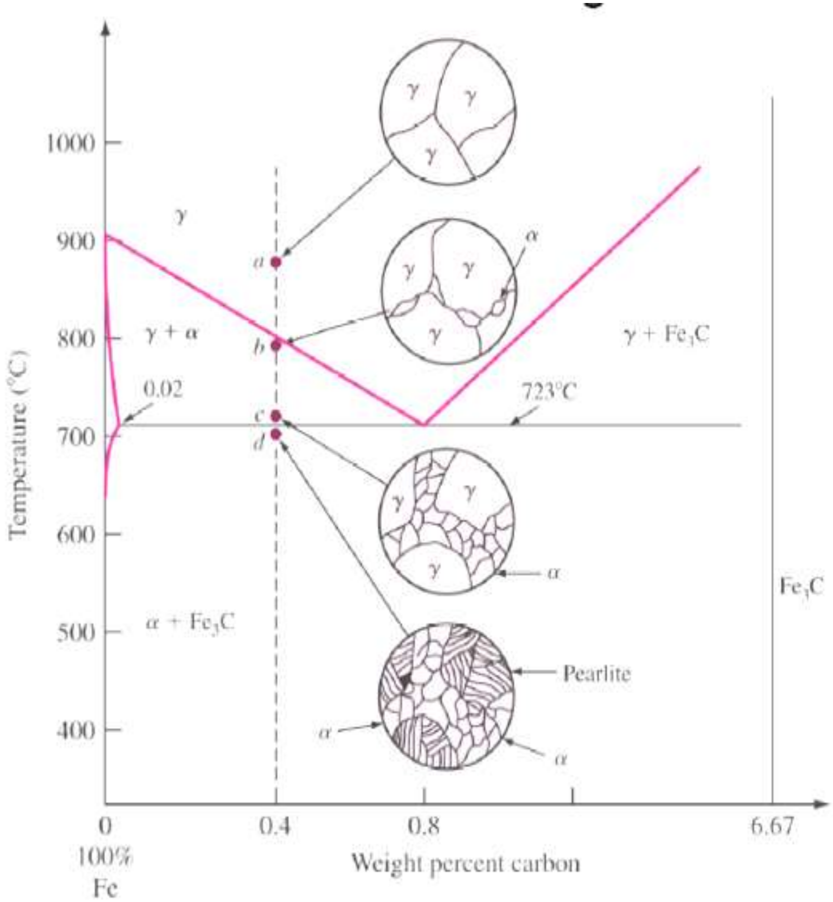

Proeutectic α = 24%
Liquid = 76%
100% Liquid
Eutectic α
Eutectic β
Alloy 2
Alloy 1
327
300
250
200
150
100
50
Solidus
Liquidus
a
b
c
d
e
Liquid
Liquidus
α
α + liquid
β + liquid
Solidus
β
Solvus
183
Eutectic point
α + β
Proeutectic α = 51%
Liquid = 49%
Temperature, °C
Proeutectic α
Solvus
19.2
40.0
61.9
97.5
0
100% Pb
10
20
30
40
50
60
70
80
90
100% Sn
Eutectic β
Eutectic α
Weight percent tin

Example Problem

For a 99.6 wt% Fe-0.40 wt% C steel at a temperature just below the eutectoid, determine the following:

a) The compositions of Fe_3C and ferrite (α).

b) The amount of cementite (in grams) that forms in 100 g of steel.



Solution to Example Problem

a) Using the RS tie line just below the eutectoid

C_α = 0.022 wt% C
C_{Fe_3C} = 6.70 wt% C

b) Using the lever rule with the tie line shown

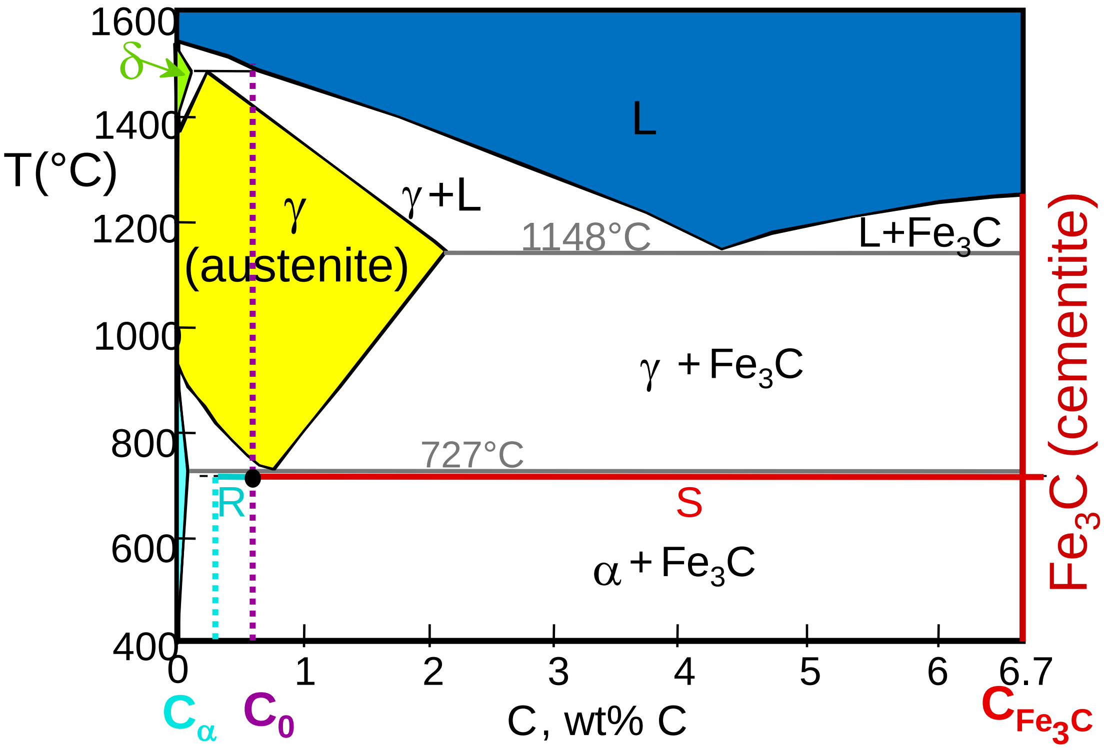
$$W_{Fe_3C} = \frac{R}{R+S} = \frac{C_0 - C_\alpha}{C_{Fe_3C} - C_\alpha}$$

$$= \frac{0.40 - 0.022}{6.70 - 0.022} = 0.057$$

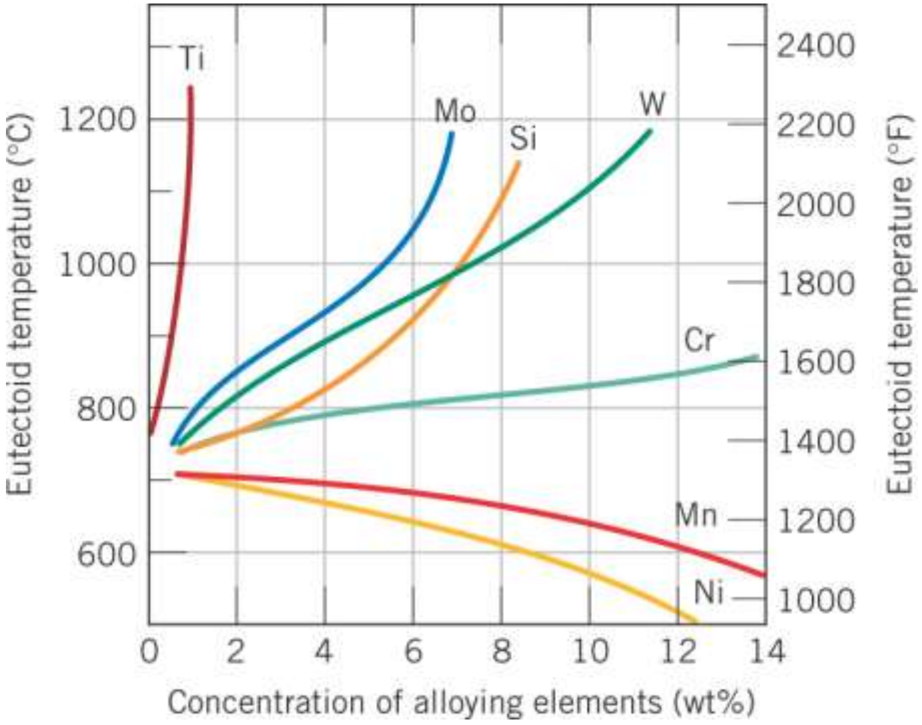
Amount of Fe_3C in 100 g

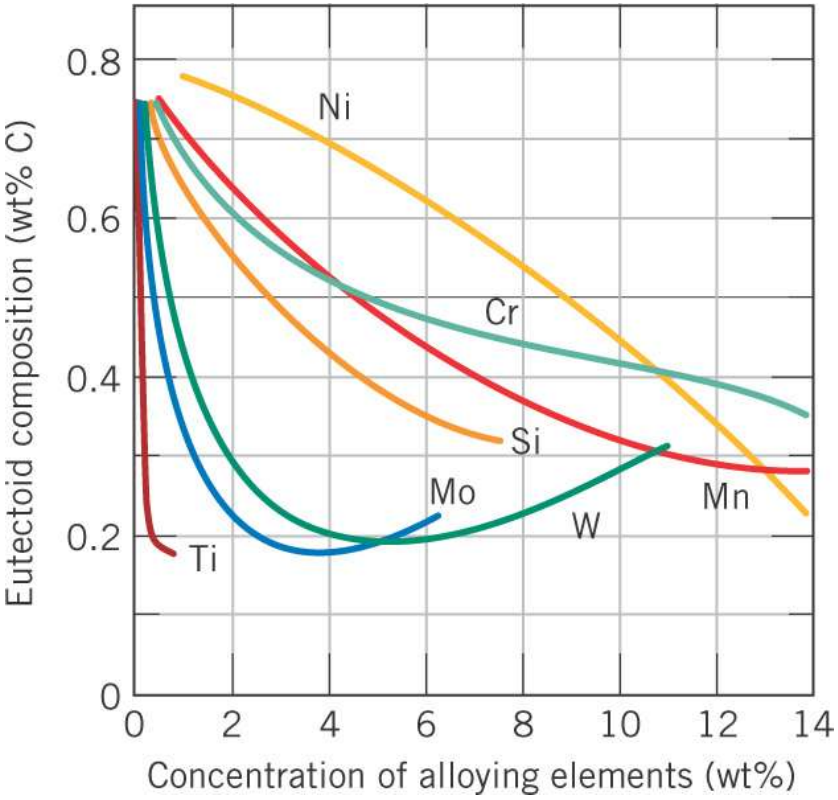
= (100 g)W_{Fe_3C}

= (100 g)(0.057) = **5.7 g**



Alloying steel with other elements changes the Eutectoid Temperature, Position of phase boundaries and relative Amounts of each phase





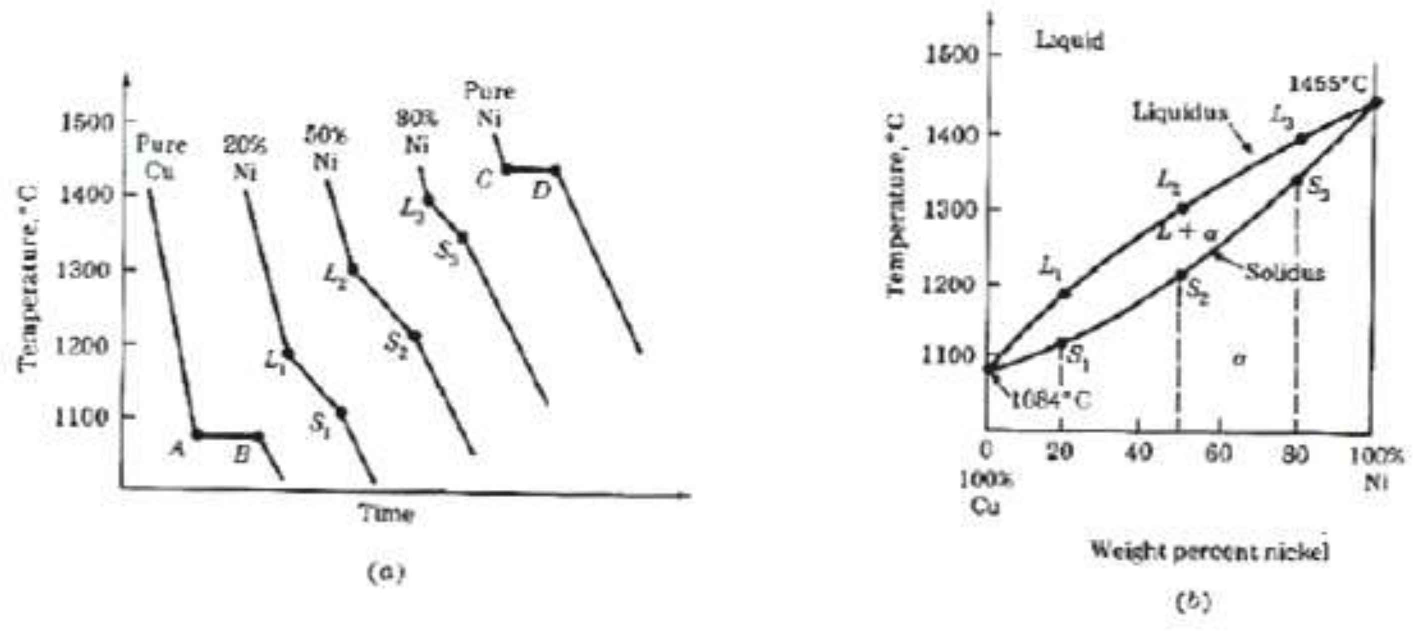
Working with Phase Diagrams

- Overall Composition
- Solidus
- Liquidus
- Limits of Solid Solubility
- Chemical Composition of Phases at any temperature
- Amount of Phases at any temperature
- Invariant Reactions
- Development of Microstructure
- Chemical Activity

Determination of Phase Diagrams

- Cooling Curves
- Differential Scanning Calorimetry
- Thermomechanical Analysis
- Differential Thermal Analysis
- Metallography/Petrography
- Energy Dispersive X-ray Spectroscopy
- Electron Microprobe Analyzer
- X-ray Diffraction
- Transmission Electron Microscopy

Cooling Curves



Using Phase Diagrams to determine Heat Treatability

- Heat Treatment is based on "controlling" the solid state transformation rate
  - Heat treatment of steels: control of the eutectoid reaction
  - Age hardening (precipitation strengthening) of aluminum alloys: control of precipitation reaction

Heat Treatment of Steels

- The eutectoid reaction
- Martensite
- Austenite
- Pearlite
- TTT diagrams

Summary

- Phase diagrams are useful tools to determine:

  -- the number and types of phases present,
  -- the composition of each phase,
  -- and the weight fraction of each phase

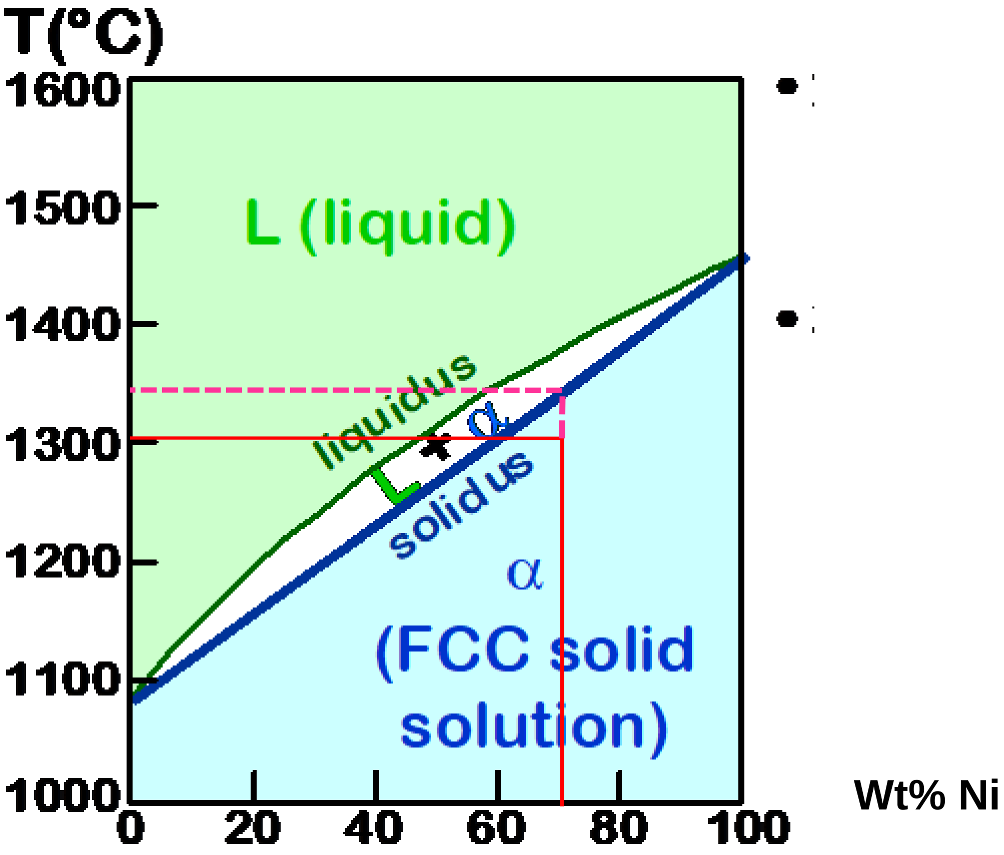
  For a given temperature and composition of the system.

- The microstructure of an alloy depends on

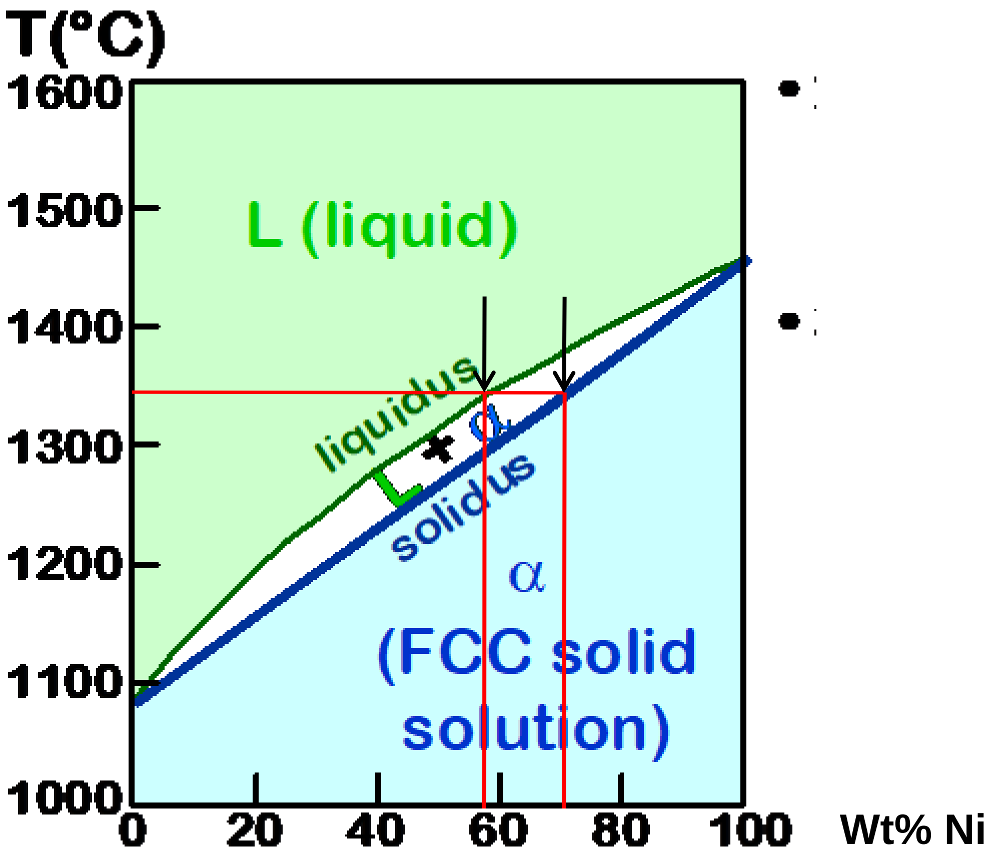
  -- its composition, and
  -- rate of cooling equilibrium

Review

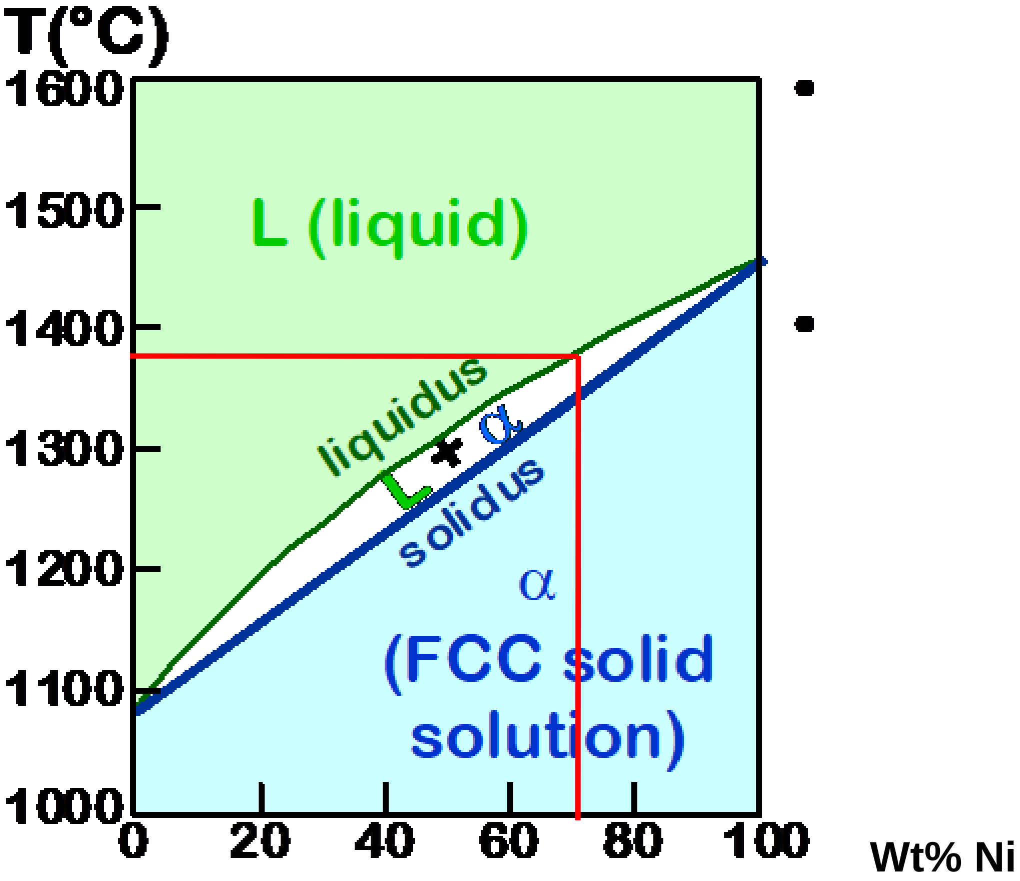
- Heating a copper-nickel alloy of composition 70 wt% Ni-30 wt% Cu from 1300°C. At what temperature does the first liquid phase form?
- Solidus - Temperature where alloy is completely solid. Above this line, liquefaction begins.
- Answer: The first liquid forms at the temperature where a vertical line at this composition intersects the α-(α + *L*) phase boundary--i.e., about 1350°C;



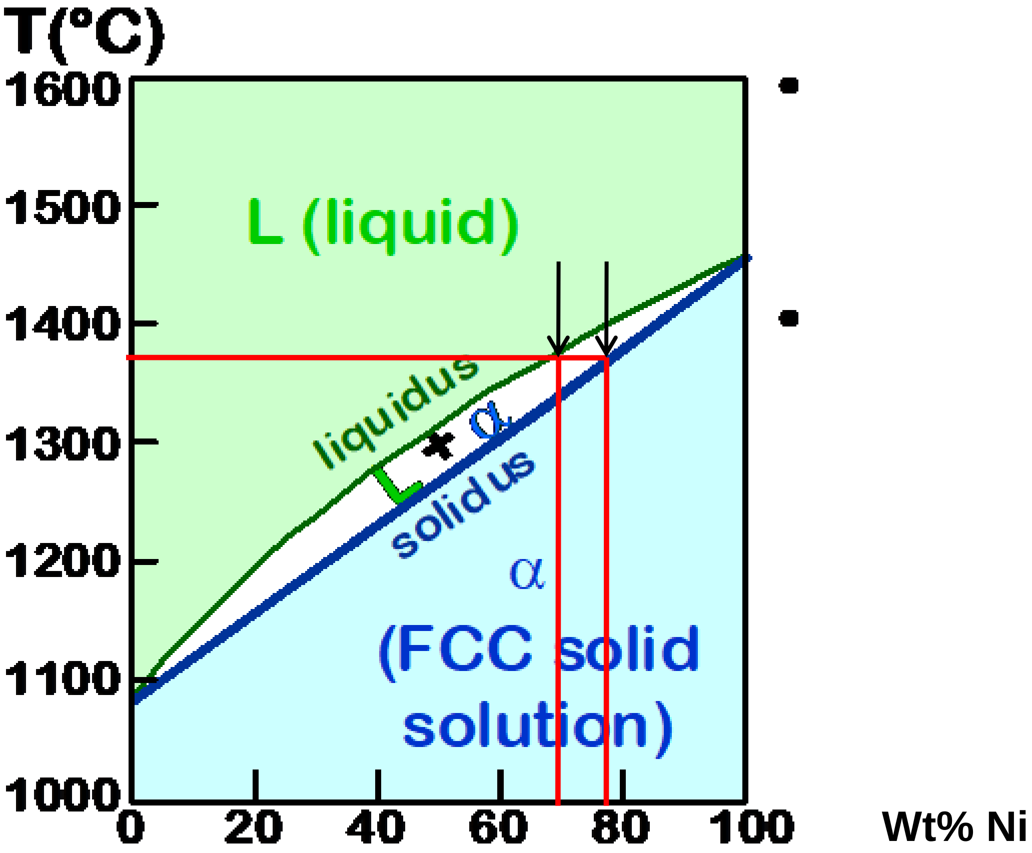
- (b) What is the composition of this liquid phase?
- Answer: The composition of this liquid phase corresponds to the intersection with the (α + *L*)-*L* phase boundary, of a tie line constructed across the α + *L* phase region at 1350°C, 59 wt% Ni;



- (c) At what temperature does complete melting of the alloy occur?
- Liquidus - Temperature where alloy is completely liquid. Below this line, solidification begins.
- Answer: Complete melting of the alloy occurs at the intersection of this same vertical line at 70 wt% Ni with the (α + *L*)-*L* phase boundary--i.e., about 1380°C;



- (d) What is the composition of the last solid remaining prior to complete melting?
- Answer: The composition of the last solid remaining prior to complete melting corresponds to the intersection with α-(α + *L*) phase boundary, of the tie line constructed across the α + *L* phase region at 1380°C--i.e., about 78 wt% Ni.

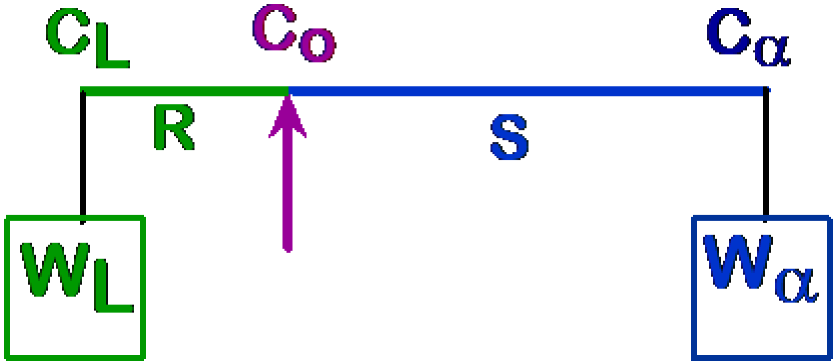


THE LEVER RULE: A PROOF

- **Sum of weight fractions:** $W_L + W_\alpha = 1$
- **Conservation of mass (Ni):** $C_o = W_L C_L + W_\alpha C_\alpha$
- **Combine above equations:**

$$\boxed{W_L = \frac{C_\alpha - C_o}{C_\alpha - C_L} = \frac{S}{R+S}} \qquad \boxed{W_\alpha = \frac{C_o - C_L}{C_\alpha - C_L} = \frac{R}{R+S}}$$

- **A geometric interpretation:**



moment equilibrium:

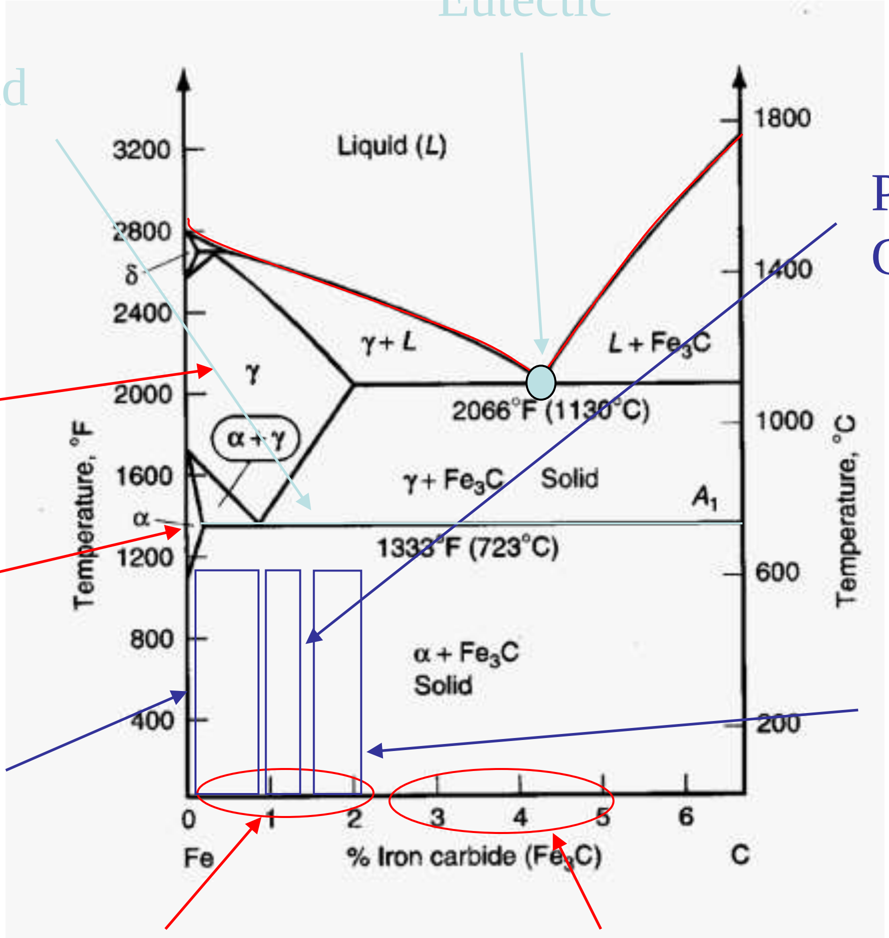
$$\boxed{W_L} R = W_\alpha S$$

$$\boxed{1 - W_\alpha}$$

solving gives Lever Rule

IRON IRON-CARBON DIAGRAM

IRON IRON-CARBON DIAGRAM



Eutectic

eutectoid

Pearlite and Cementine

Austenite

Ferrite

Pearlite and Carbide

Pearlite

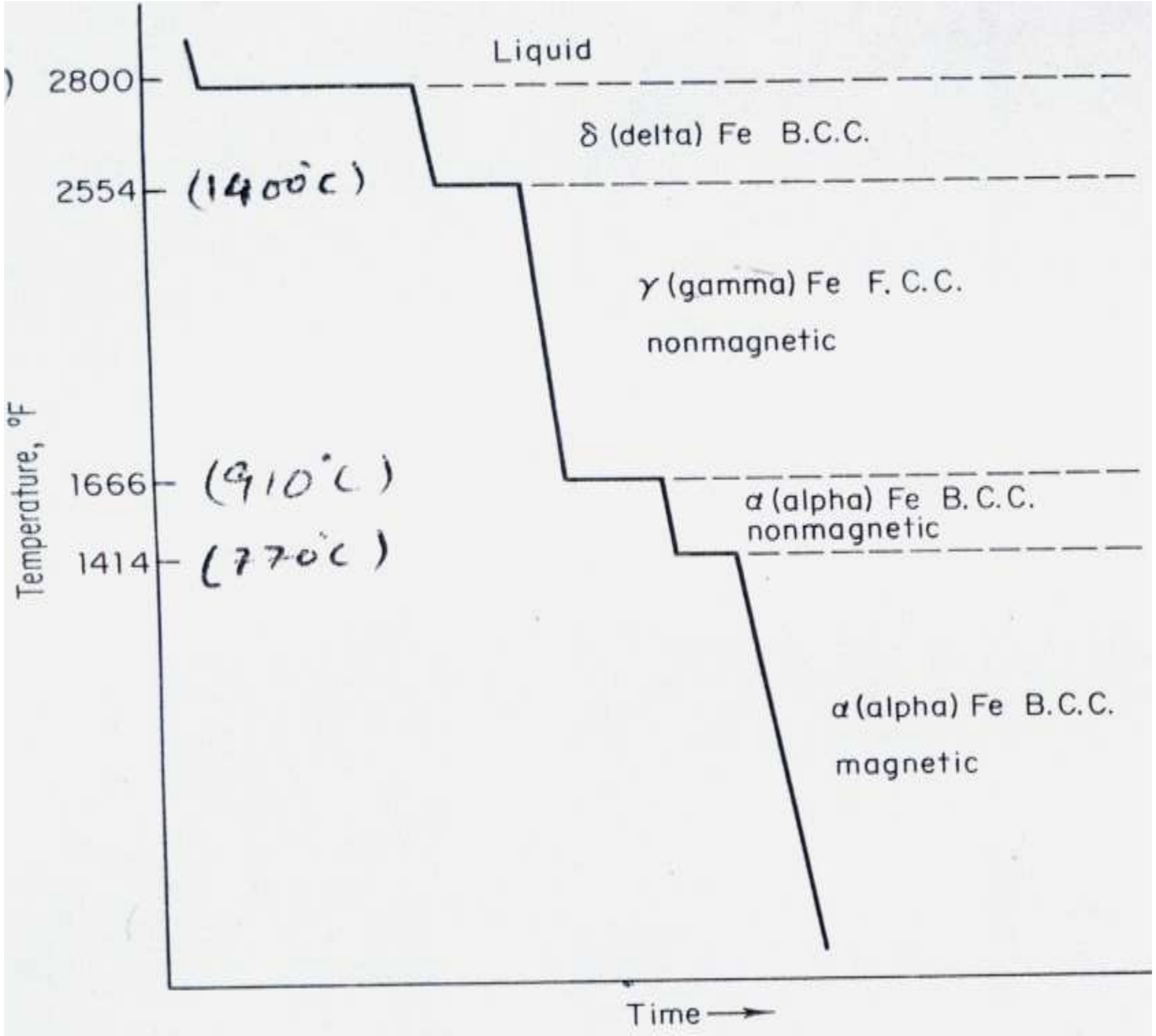
Steel

Cast iron

Outline

- Introduction
- Cooling curve for pure iron
- Definition of structures
- Iron-Carbon equilibrium phase diagram – Sketch
- The Iron-Iron Carbide Diagram - Explanation
- The Austenite to ferrite / cementite transformation
- Nucleation & growth of pearlite
- Effect of C %age on the microstructure of steel
- Relationship b/w C %age & mechanical properties of steel

Cooling curve for pure iron

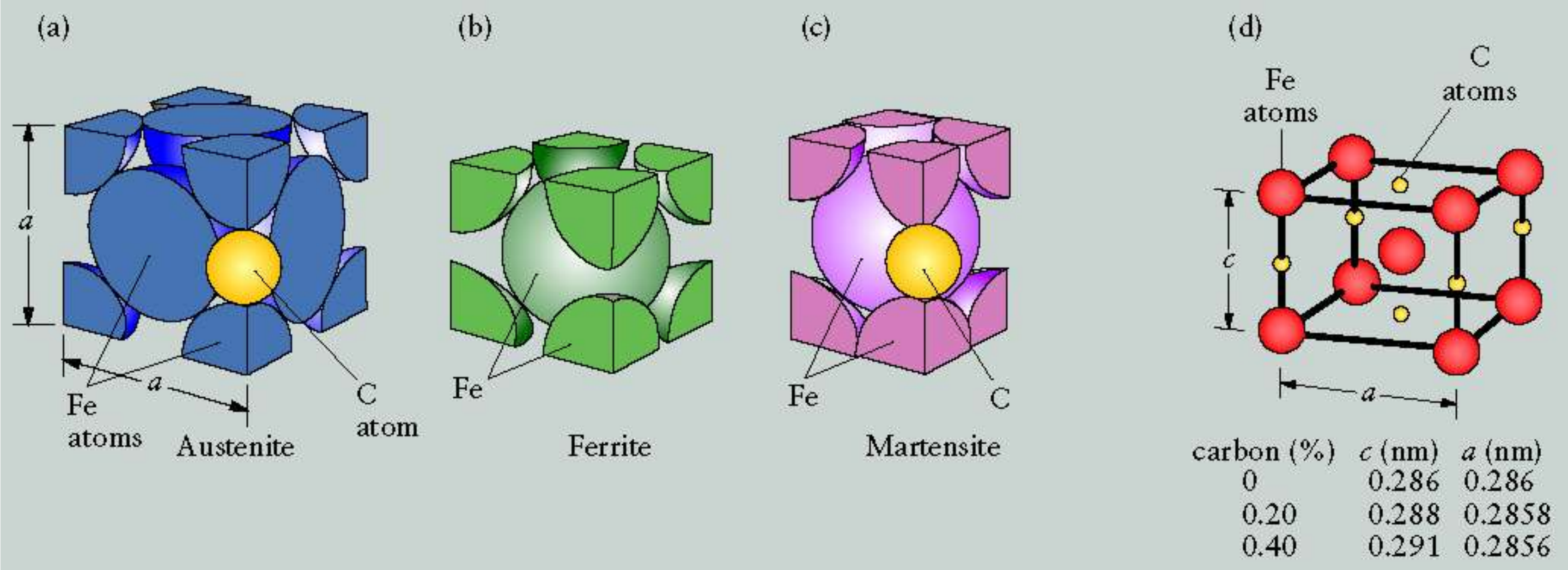


Definition of structures

Various phases that appear on the Iron-Carbon equilibrium phase diagram are as under:

- Austenite
- Ferrite
- Pearlite
- Cementite
- Martensite*
- Ledeburite

Unit Cells of Various Metals



carbon (%)	c (nm)	a (nm)
0	0.286	0.286
0.20	0.288	0.2858
0.40	0.291	0.2856

- FIGURE - The unit cell for (a) austentite, (b) ferrite, and (c) martensite. The effect of the percentage of carbon (by weight) on the lattice dimensions for martensite is shown in (d). Note the interstitial position of the carbon atoms and the increase in dimension *c* with increasing carbon content. Thus, the unit cell of martensite is in the shape of a rectangular prism.

Microstructure of different phases of steel

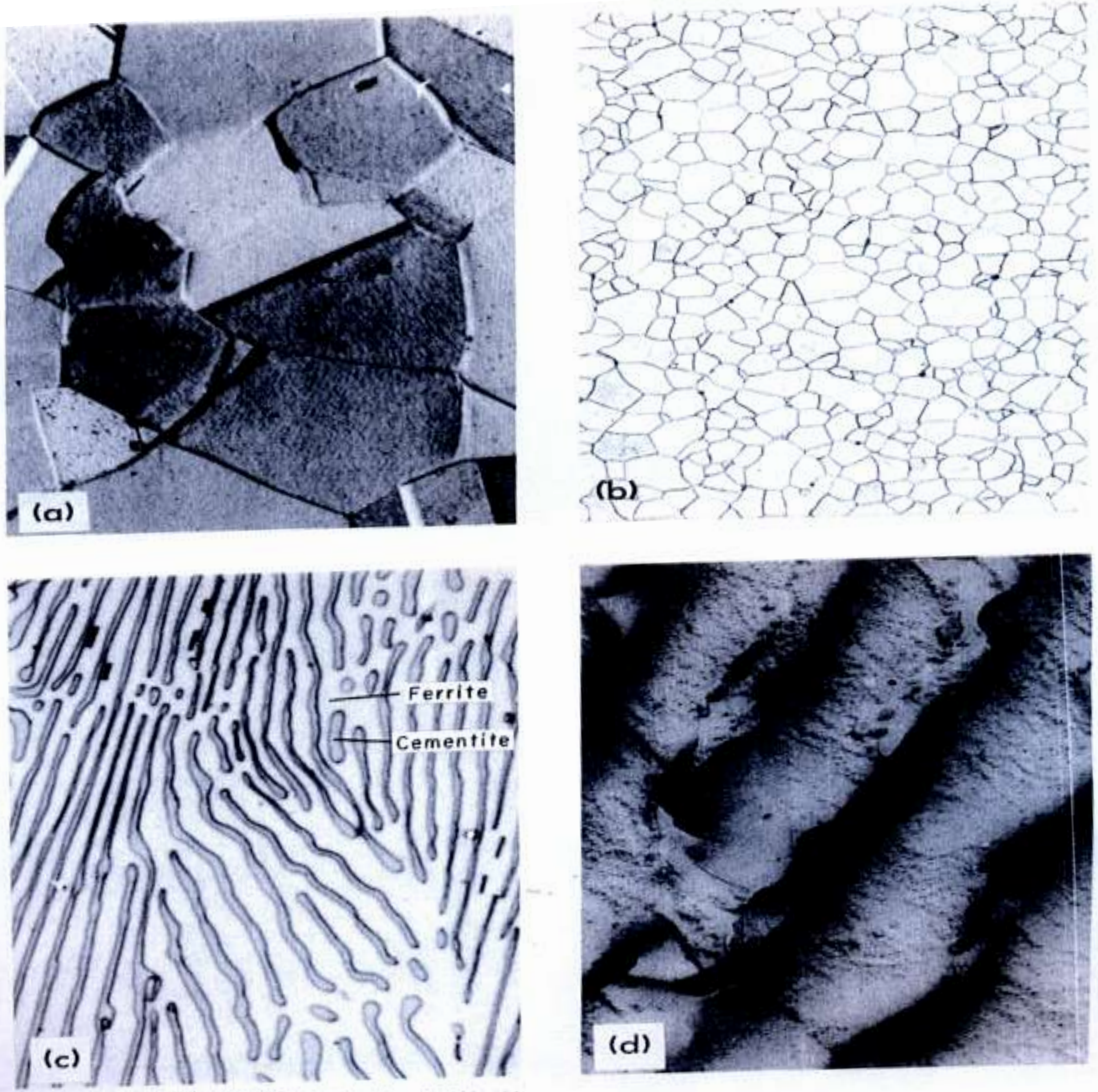
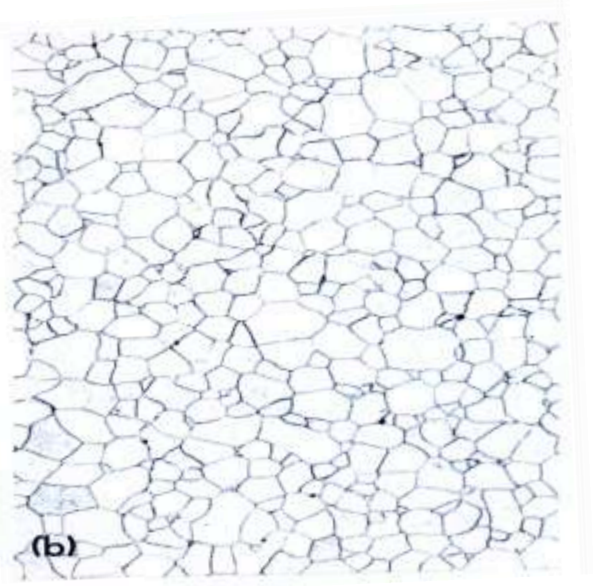


Fig. 7·8 The microstructure of (*a*) austenite, 500X; (*b*) ferrite, 100X; (*c*) pearlite, 2,500X; (*d*) pearlite, electron micrograph, 17,000X; enlarged 3X in printing. (*a*, *b*, and *c*, Research Laboratory, U.S. Steel Corporation.)

Definition of structures

- **Ferrite** is known as *α* solid solution.
- It is an interstitial solid solution of a small amount of carbon dissolved in *α* (BCC) iron.
- stable form of iron below 912 deg.C
- The maximum solubility is 0.025 % C at 723°C and it dissolves only 0.008 % C at room temperature.
- It is the softest structure that appears on the diagram.

Definition of structu



Ferrite

- Average properties are:
  - – Tensile strength = 40,000 psi
  - – Elongation = 40 % in 2 in;
  - – Hardness > Rockwell C 0 or
    > Rockwell B 90

Definition of structures

- **Pearlite** is the eutectoid mixture containing 0.80 % C and is formed at 723°C on very slow cooling.
- It is a very fine platelike or lamellar mixture of ferrite and cementite.
- The white ferritic background or matrix contains thin plates of cementite (dark).

Definition of structures

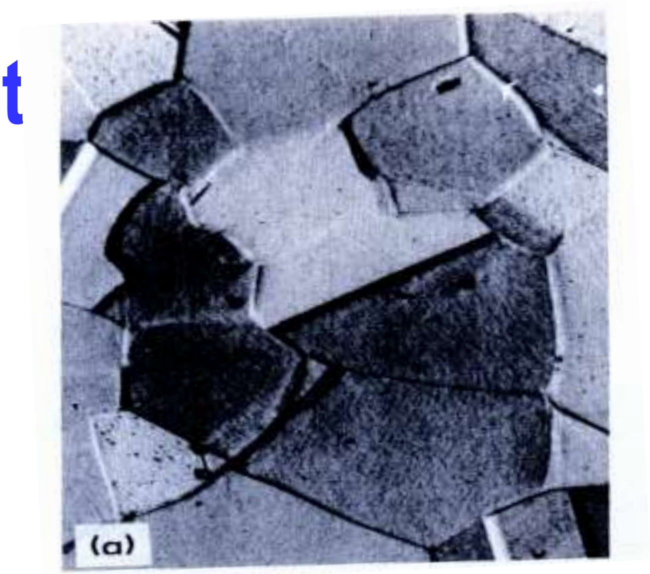
Pearlite

- Average properties are:
  - Tensile strength = 120,000 psi;
  - Elongation = 20 % in 2 in.;
  - Hardness = Rockwell C 20, Rock-well B 95-100, or BHN 250-300.

Definition of structures

- **Austenite** is an interstitial solid solution of Carbon dissolved in γ (F.C.C.) iron.
- Maximum solubility is 2.0 % C at 1130°C.
- High formability, most of heat treatments begin with this single phase.
- It is normally not stable at room temperature. But, under certain conditions it is possible to obtain austenite at room temperature.

Definition of struct



Austenite

- Average properties are:
  - Tensile strength = 150,000 psi;
  - Elongation = 10 percent in 2 in.;
  - Hardness = Rockwell C 40, approx; and
  - toughness = high

Definition of structures

- **Cementite** or iron carbide, is very hard, brittle intermetallic compound of iron & carbon, as Fe_3C, contains 6.67 % C.
- It is the hardest structure that appears on the diagram, exact melting point unknown.
- Its crystal structure is orthorhombic.
- It is has
  - low tensile strength (approx. 5,000 psi), but
  - high compressive strength.

Definition of structures

- **Ledeburite** is the eutectic mixture of austenite and cementite.
- It contains 4.3 percent C and is formed at 1130°C.

Definition of structures

❿ **Martensite** - a super-saturated solid solution of carbon in ferrite.

❿ It is formed when steel is cooled so rapidly that the change from austenite to pearlite is suppressed.

❿ The interstitial carbon atoms distort the BCC ferrite into a BC-tetragonal structure (BCT).; responsible for the hardness of quenched steel

The Iron-Iron Carbide Diagram

- A map of the temperature at which different phase changes occur on very slow heating and cooling in relation to Carbon, is called Iron- Carbon Diagram.
- Iron- Carbon diagram shows
  - the type of alloys formed under very slow cooling,
  - proper heat-treatment temperature and
  - how the properties of steels and cast irons can be radically changed by heat-treatment.

Various Features of Fe-C diagram

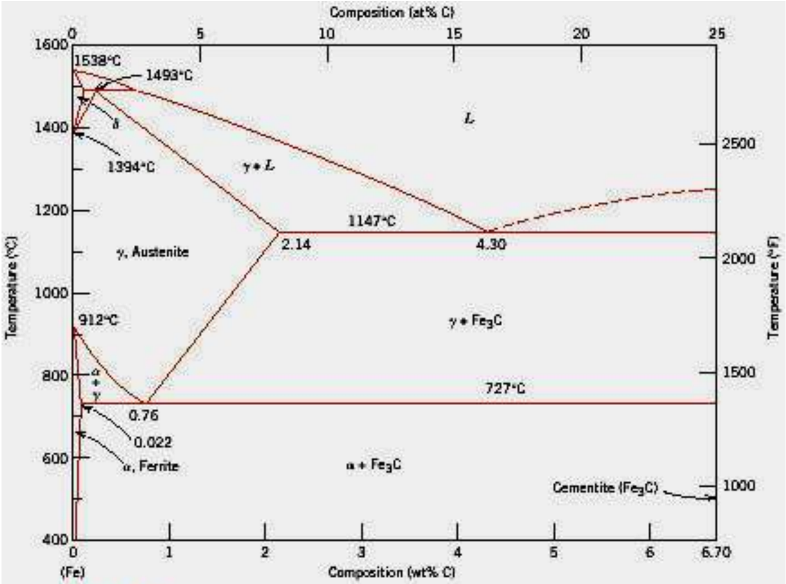


FIGURE 9.22 The iron–iron carbide phase diagram. (Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski, Editor-in-Chief, 1990. Reprinted by permission of ASM International, Materials Park, OH.)

Phases present

L

δ
BCC structure
Paramagnetic

α ferrite
BCC structure
Ferromagnetic
Fairly ductile

γ austenite
FCC structure
Non-magnetic
ductile

Fe_3C cementite
Orthorhombic
Hard
brittle

Reactions

Peritectic L + δ = γ

Eutectic L = γ + Fe_3C

Eutectoid γ = α + Fe_3C

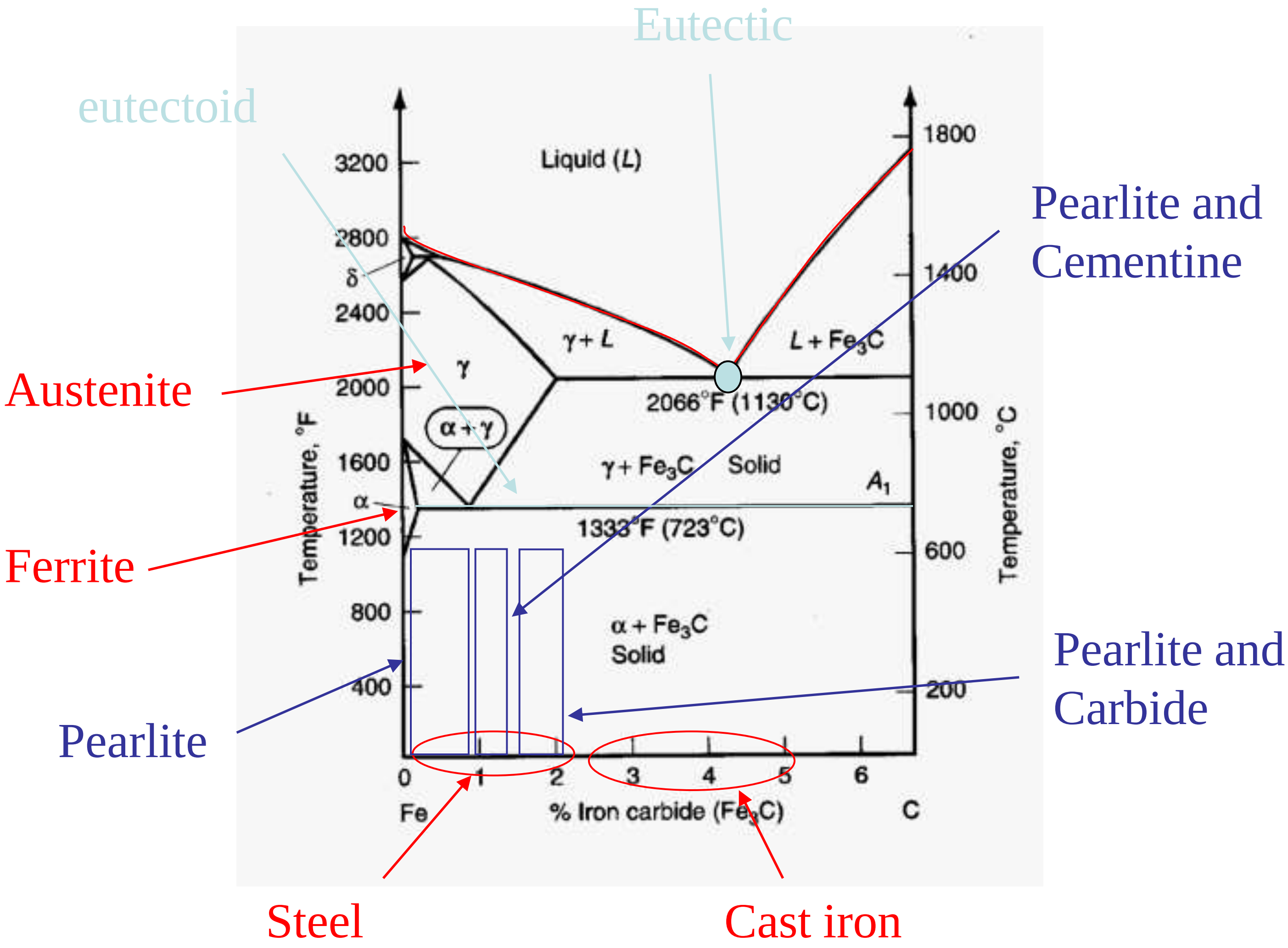
Max. solubility of C in ferrite=0.022%

Max. solubility of C in austenite=2.11%

Three Phase Reactions

- Peritectic, at 1490 deg.C, with low wt% C alloys (almost no engineering importance).
- Eutectic, at 1130 deg.C, with 4.3wt% C, alloys called cast irons.
- Eutectoid, at 723 deg.C with eutectoid composition of 0.8wt% C, two-phase mixture (ferrite & cementite). They are steels.

How to read the Fe-C phase diagram



Eutectic

eutectoid

Pearlite and Cementine

Austenite

Ferrite

Pearlite and Carbide

Pearlite

Steel

Cast iron

The Iron-Iron Carbide Diagram

The diagram shows three horizontal lines which indicate isothermal reactions (on cooling / heating):

- First horizontal line is at 1490°C, where peritectic reaction takes place:

  Liquid + δ ↔ austenite

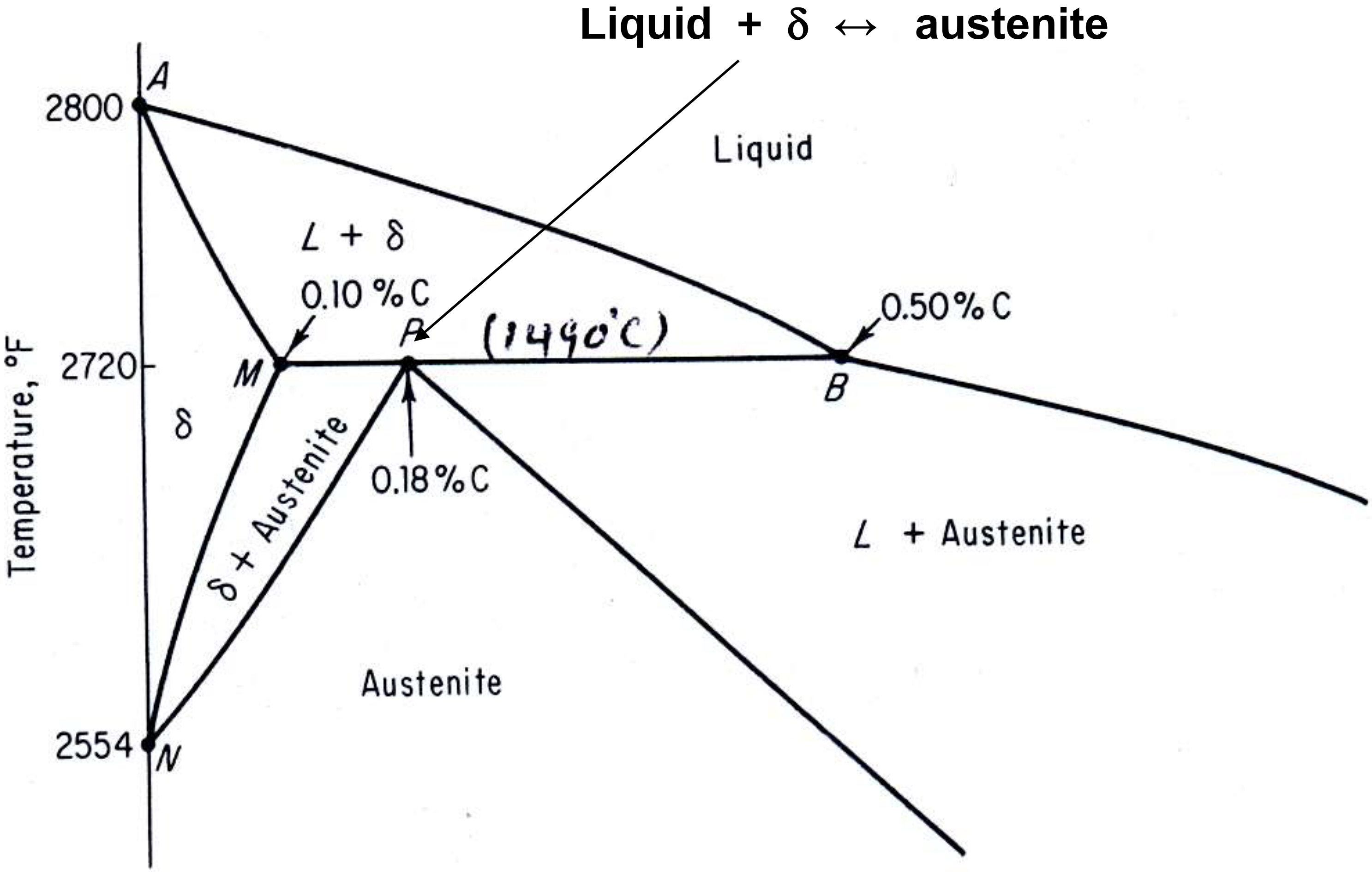
- Second horizontal line is at 1130°C, where eutectic reaction takes place:

  liquid ↔ austenite + cementite

- Third horizontal line is at 723°C, where eutectoid reaction takes place:

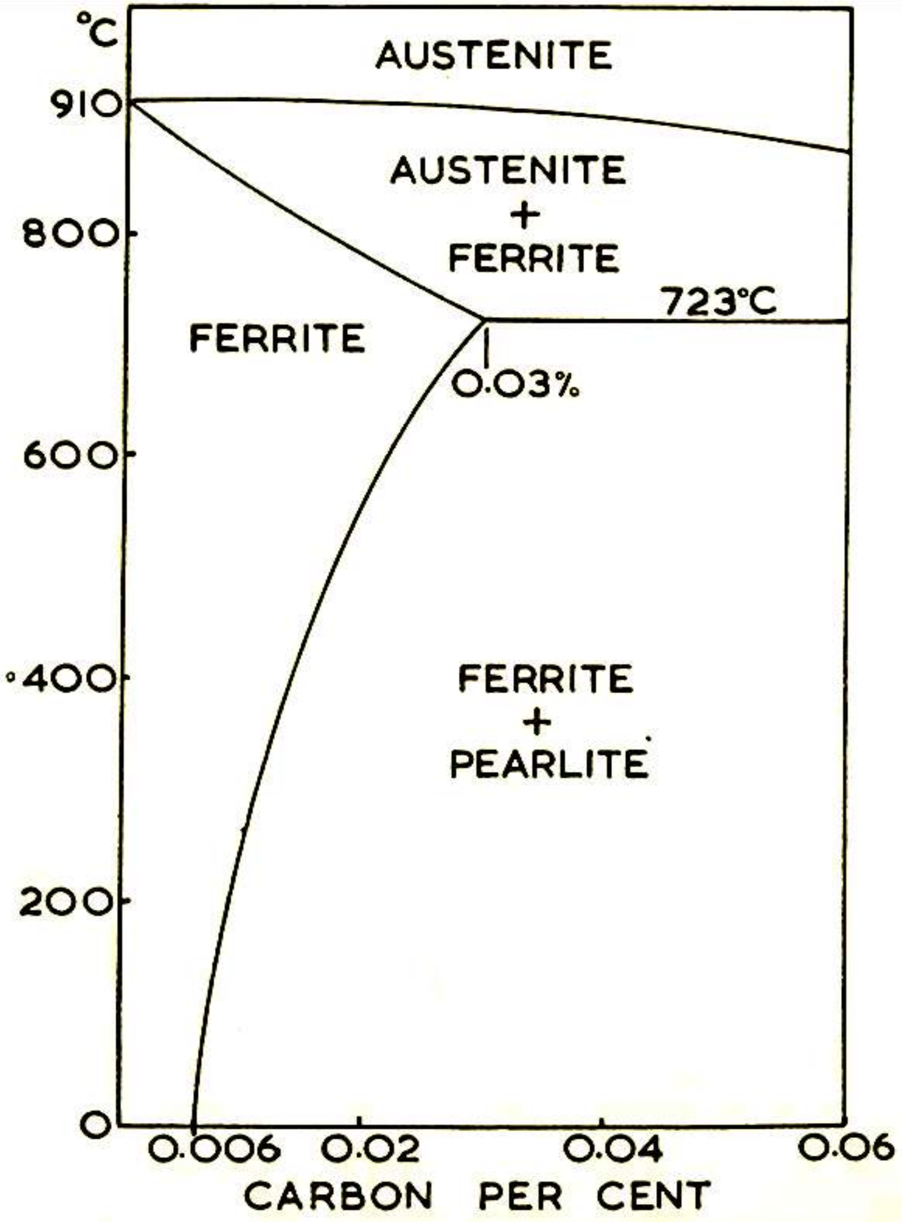
  austenite ↔ pearlite (mixture of ferrite & cementite)

Delta region of Fe-Fe carbide diagram



Liquid + δ ↔ austenite

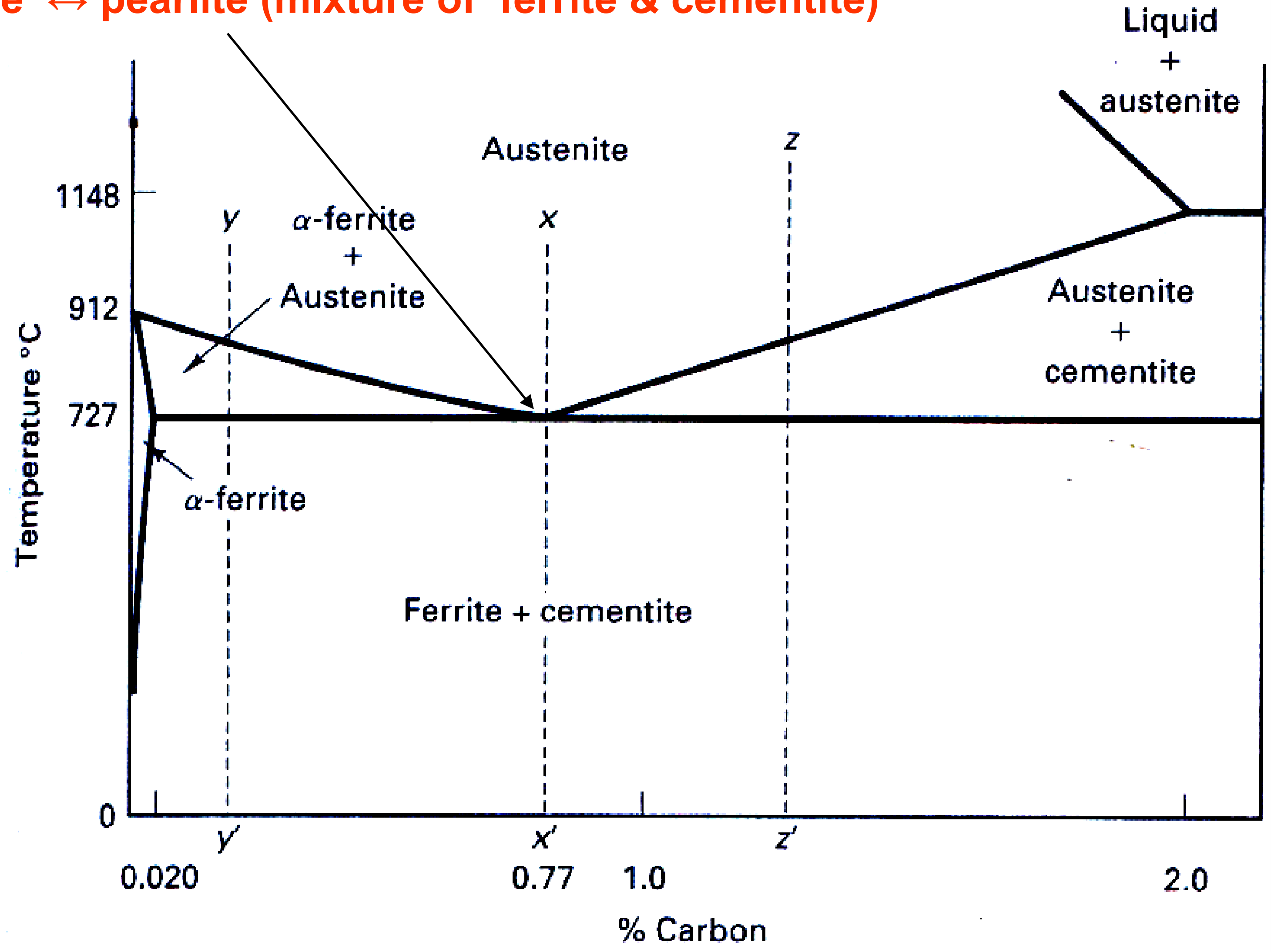
Ferrite region of Fe-Fe Carbide diagram



2.—The "Ferrite Area" of the Iron–Carbon Equilibrium Diagram, Showing the Extent to Which Carbon is Soluble in α Iron.

Simplified Iron-Carbon phase diagram

austenite ↔ pearlite (mixture of ferrite & cementite)



The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

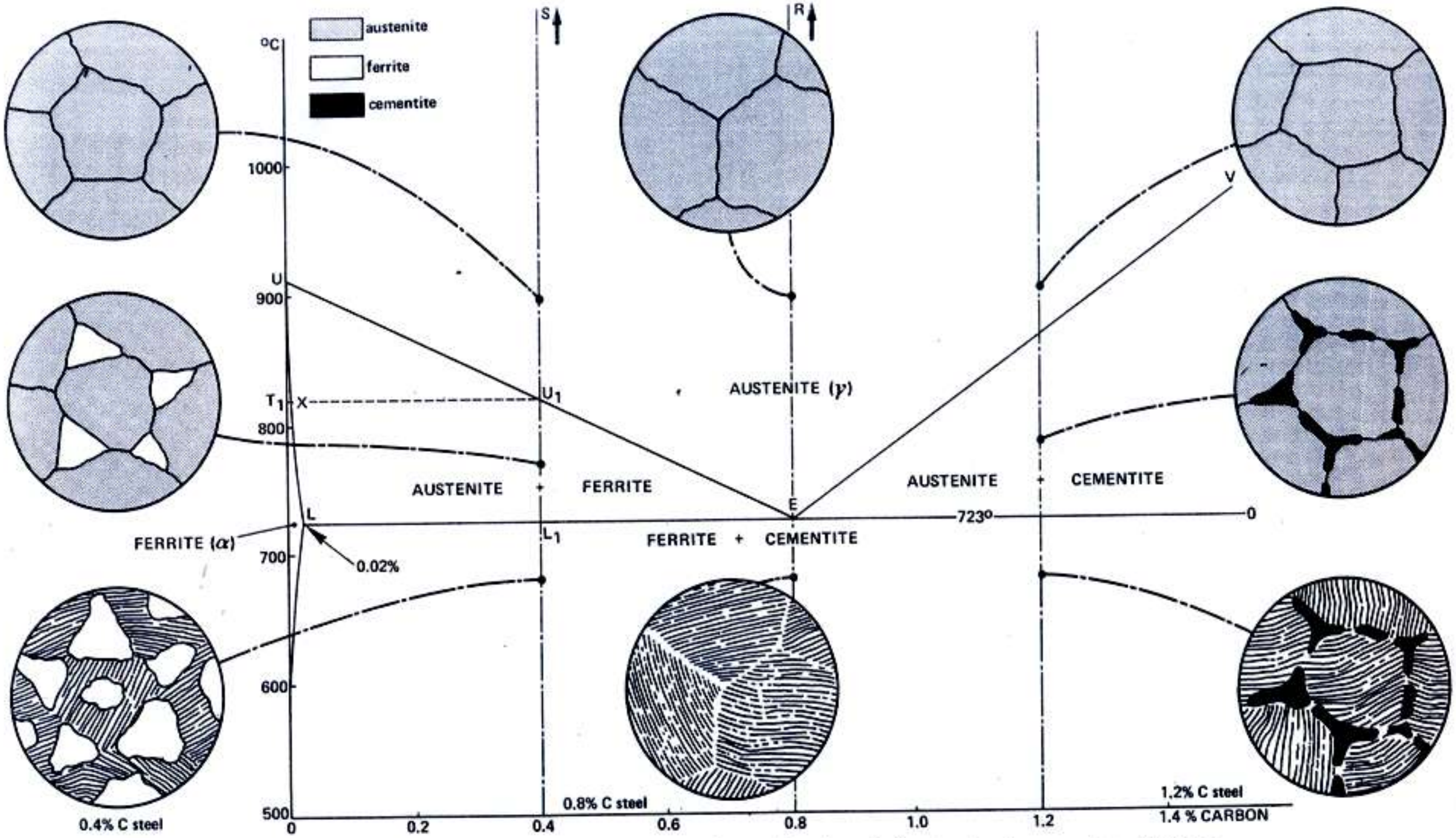


Fig. 9.3—The austenite → ferrite/cementite transformation in relation to the iron–carbon diagram.

The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

In order to understand the transformation processes, consider a steel of the eutectoid composition. 0.8% carbon, being slow cooled along line *x-x'.*

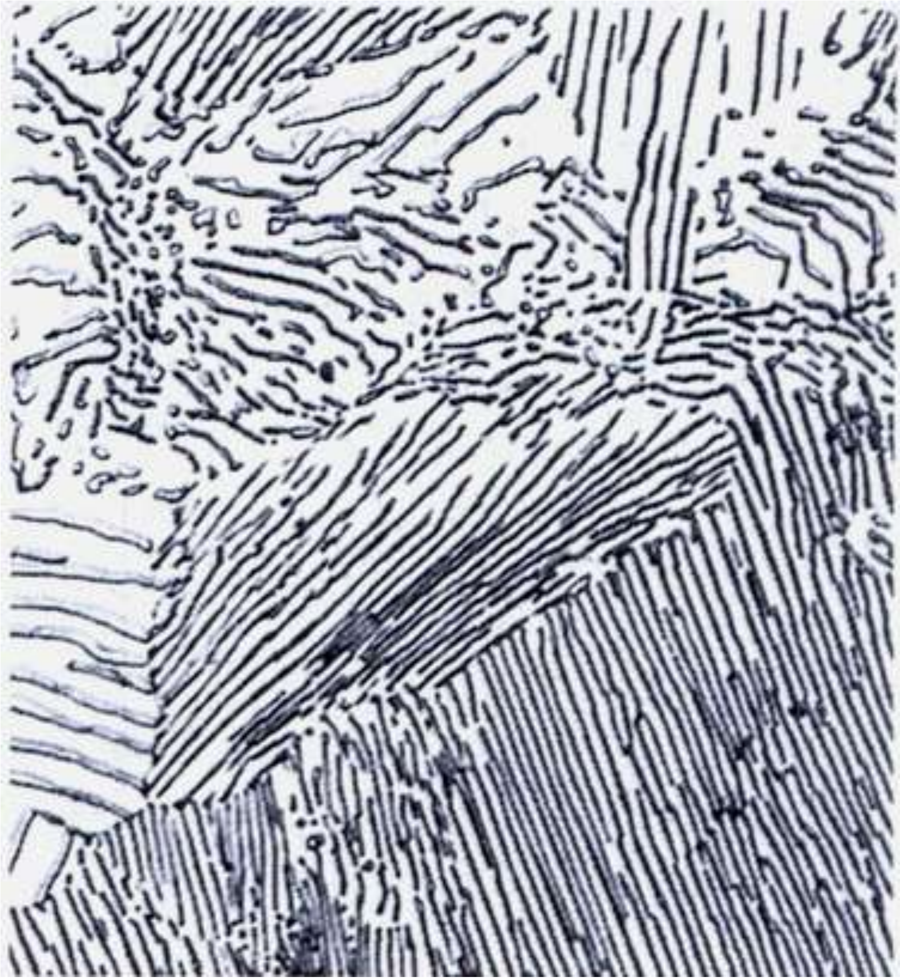
- At the upper temperatures, only austenite is present, with the 0.8% carbon being dissolved in solid solution within the FCC. When the steel cools through 723°C, several changes occur simultaneously.

The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

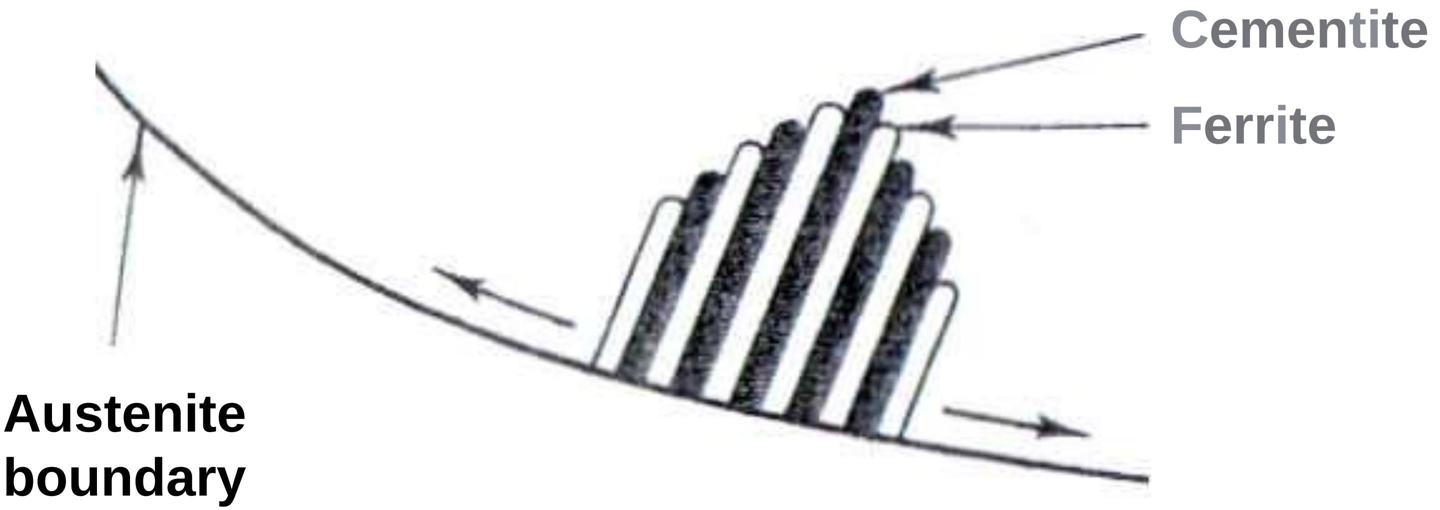
- The iron wants to change crystal structure from the FCC austenite to the BCC ferrite, but the ferrite can only contain 0.02% carbon in solid solution.
- The excess carbon is rejected and forms the carbon-rich intermetallic known as cementite.

Pearlitic structure

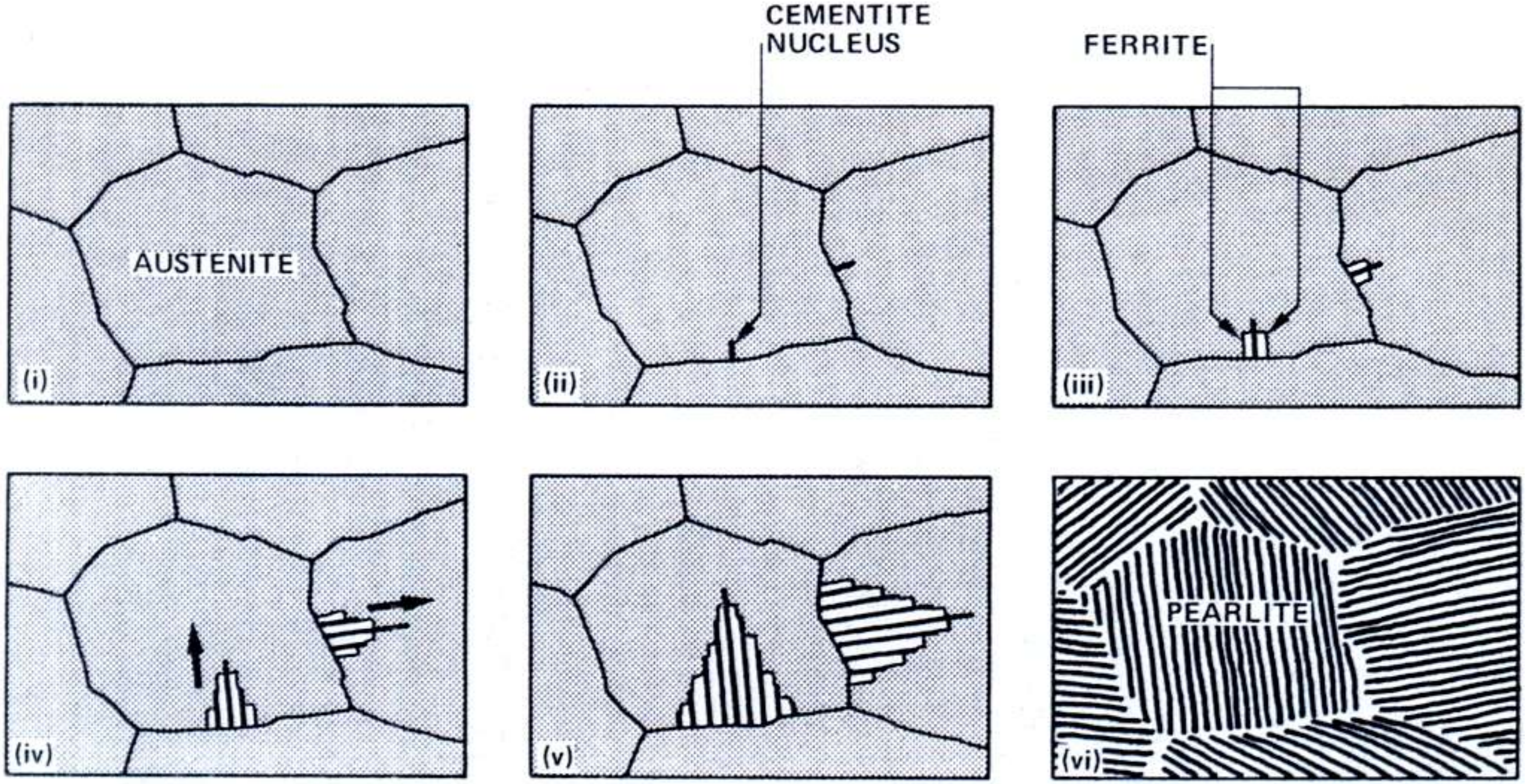
- The net reaction at the eutectoid is the formation of pearlitic structure.
- Since the chemical separation occurs entirely within crystalline solids, the resultant structure is a fine mixture of ferrite and cementite.



Schematic picture of the formation and growth of pearlite



Nucleation & growth of pearlite

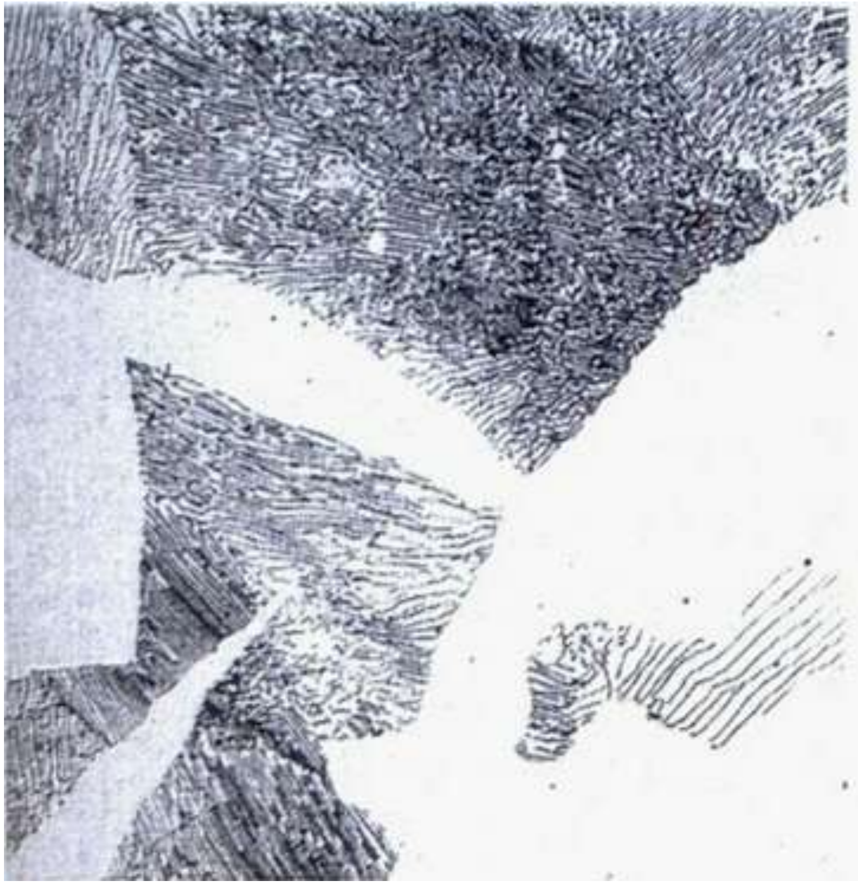


The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

- **Hypo-eutectoid steels:** Steels having less than 0.8% carbon are called *hypo-eutectoid steels* (*hypo* means "less than").
- Consider the cooling of a typical hypo-eutectoid alloy along line *y-y‘.*
- At high temperatures the material is entirely austenite.
- Upon cooling it enters a region where the stable phases are ferrite and austenite.
- The low-carbon ferrite nucleates and grows, leaving the remaining austenite richer in carbon.

The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

- **Hypo-eutectoid steels-** At *723°C*, the remaining austenite will have assumed the eutectoid composition *(0.8%* carbon), and further cooling transforms it to pearlite.
- The resulting structure, is a mixture of *primary* or *pro-eutectoid ferrite* (ferrite that forms before the eutectoid reaction) and regions of pearlite.



The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

- **Hyper-eutectoid steels** (*hyper* means "greater than") are those that contain more than the eutectoid amount of Carbon.
- When such a steel cools, as along line *z-z'* , the process is similar to the hypo-eutectoid steel, except that the primary or pro-eutectoid phase is now cementite instead of ferrite.

The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

- As the carbon-rich phase nucleates and grows, the remaining austenite decreases in carbon content, again reaching the eutectoid composition at 723°C.
- This austenite transforms to pearlite upon slow cooling through the eutectoid temperature.
- The resulting structure consists of primary cementite and pearlite.
- The continuous network of primary cementite will cause the material to be extremely brittle.

The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

Hypo-eutectoid steel showing primary cementite along grain boundaries pearlite

The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

- It should be noted that the transitions as discussed, are for equilibrium conditions, as a result of slow cooling.
- Upon slow heating the transitions will occur in the reverse manner.

The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

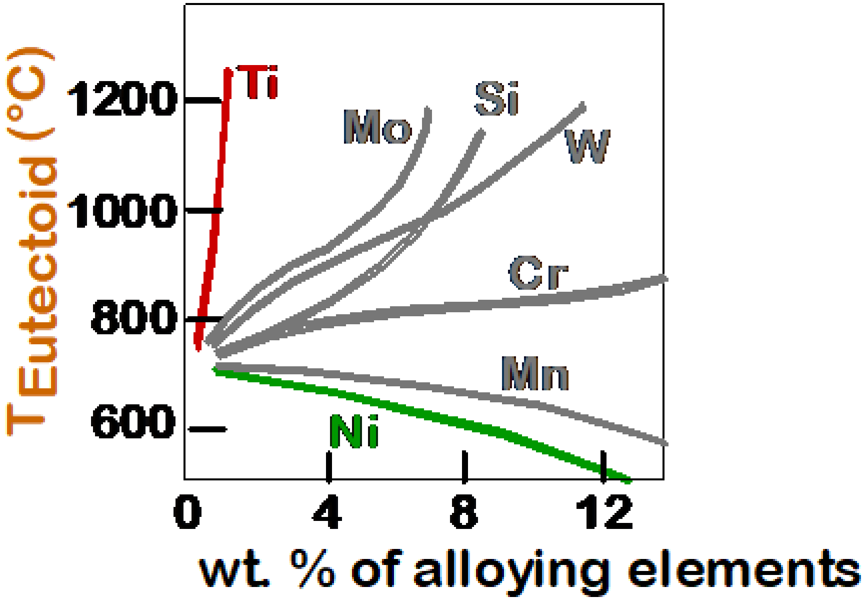
- When the alloys are cooled rapidly, entirely different results are obtained, since sufficient time may not be provided for the normal phase reactions to occur.
- In these cases, the equilibrium phase diagram is no longer a valid tool for engineering analysis.
- Rapid-cool processes are important in the heat treatment of steels and other metals (to be discussed later in H/T of steels).

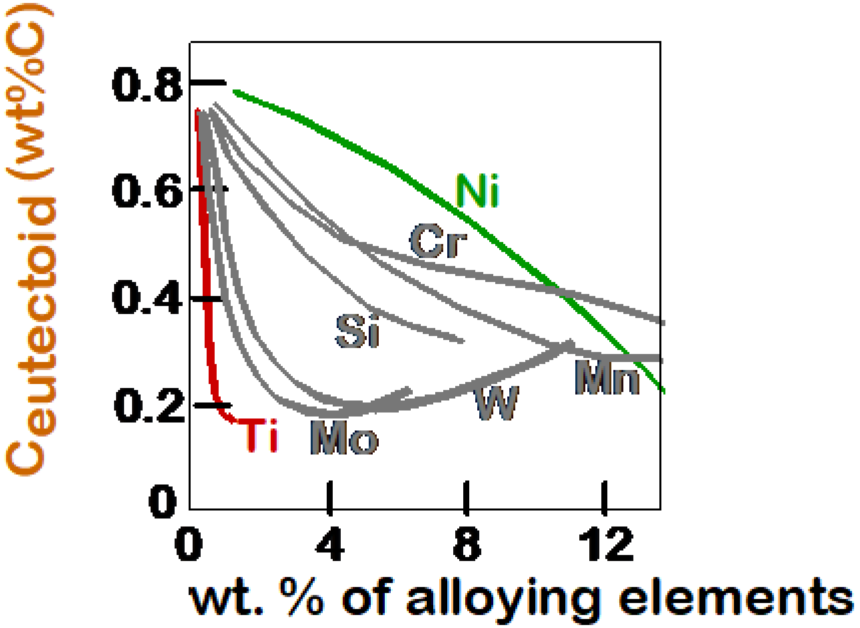
Principal phases of steel and their Characteristics

Phase	Crystal structure	Characteristics
Ferrite	BCC	Soft, ductile, magnetic
Austenite	FCC	Soft, moderate strength, non-magnetic
Cementite	Compound of Iron & Carbon Fe_3C	Hard &brittle

Alloying Steel with more Elements

- $T_{eutectoid}$ changes:
- $C_{eutectoid}$ changes:



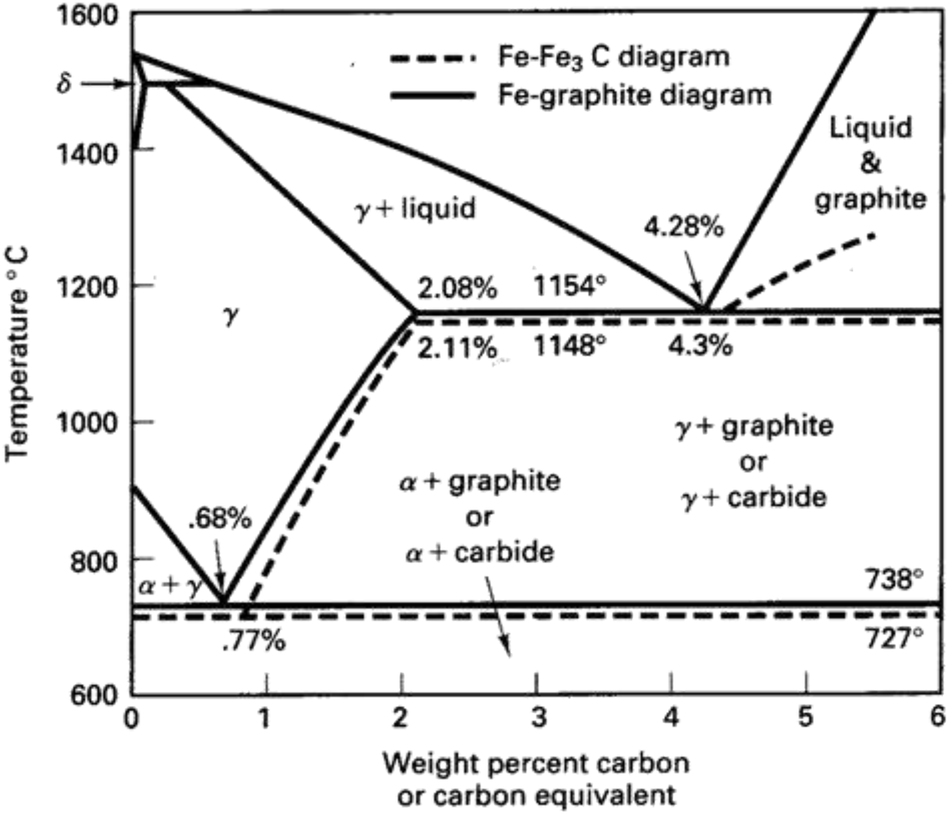


Cast Irons

-Iron-Carbon alloys of 2.11%C or more are cast irons.

-Typical composition: 2.0-4.0%C,0.5-3.0% Si, less than 1.0% Mn and less than 0.2% S.

-Si-substitutes partially for C and promotes formation of graphite as the carbon rich component instead Fe_3C.



Applications

- It is used tailor properties of steel and to heat treat them.
- It is also used for comparison of crystal structures for metallurgists in case of rupture or fatigue

STEELS

Professor in Metals Studies Priit Kulu

Department of Materials Engineering

Classification of steels (EN 10020)

- **Non-alloy steels (carbon steels)**
- **Alloy steels**

Inclusions, %	Non-alloy steels (carbon steels)	Alloy steels
Mn	≤ 1,65	> 1,8
Si	≤ 0,5	> 0,5
Cr	≤ 0,3	> 0,5
Ni	≤ 0,3	> 0,5
Ti	≤ 0,05	> 0,12
V	≤ 0,1	> 0,12

Non-alloy and alloy steels classification (1)

Non-alloy steels (carbon steels)	*Alloy steels*
C content based	Alloying degree based
- low C-steels (<0,25%)	- low alloy steels (<2,5%)
- medium C-steels (0,3…0,6%)	- medium alloy steels (<5%)
- high C-steels (>0,6%)	- high alloy steels (>5%)

Alloying degree based
- Cr steels
- Mn steels
- Cr-Ni steels etc.

Non-alloy and alloy steels (2)

Non-alloy steels (carbon steels)

Quality based (degree of purity):

- -ordinary quality
- quality steels (≤ 0,035 S,P)
- high quality steels (≤ 0,025 S,P)

Deoxidation degree based

- killed steels (Mn, ↑ Si)
- semikilled steels (Mn, ↓ Si)
- rimmed steels (Mn)

Alloy steels

Quality based:

- quality steels
- high quality steels

Structure based:

- in annealed condition
- in normalized condition (ferrite, pearlite, martensite and austenitic steels)

Non-alloy and alloy steels classification (3)

Non-alloy steels (carbon steels)

Alloy steels

Application based:

C<0,7%C – structural steels – 0,2...0,7% C

C>0,7%C – tool steels – 0,4...1,6% C

- corrosion resistant
- heat resistant
- high temperature strength
- magnetic
- cryogenic

Classification of structural steels

Non-alloy steels (carbon steels) *Alloy steels*

Heat treatment based:

- case hardening steels (≤ 0,25% C)
- quenching and tempering steels (0,3…0,6% C)

- nitriding and carbonitriding steels

  (0,1…0,2 or 0,3…0,4% C)

Designation of steels (1)

Notch impact energy

°C	KU, J		
	27	40	60
+20	JR	KR	LR
0	J0	K0	L0
-20	J2	K2	L2
-30	J3	K3	L3
-40	J4	K4	L4
-50	J5	K5	L5
-60	J6	K6	L6

Steels (EN10027)

Designations (1)

- Mechanical properties based on: R_e

– steels for steel constructions	S355J0
– steels for pressure vessel	P265B
– steels for machine constructions	E295
– steels for pipes	L360QB
– concrete reinforcing steel	B500N

- Based on: R_m

– rail steels	RO880Mn
– prestressing steels	Y1770C

Designations (2)

- **Chemical composition based**
  - **C** (non-alloy steels (carbon steels), ex free cutting steels

    C35E

    G-C35E (cast steel)

    35 – C%x100 (E – max S-content)
  - **C, alloying elements** (low- ja medium alloy steels, all. elem., ≤5%, non-alloy steels (carbon steels) Mn ≥1%, non-alloy free cutting steels)

    28Mn6

    G-28Mn6
  - **C, all. elem.** (high alloy steels, all. elem. >5%)

    X5CrNi18-10
  - **All. elem.** (high speed steels)

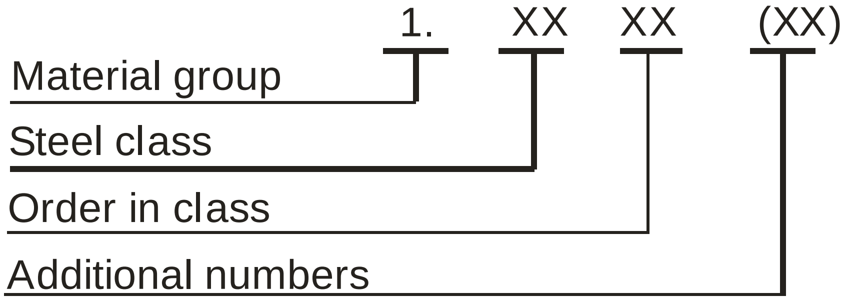
    HS 12-9-1-8

    W-Mo-V-Co

Alloying element	**Factor**
Cr, Co, Mn, Si, Ni, W	4
Al, Cu, Mo, Nb, Ti, V, Zr	10
Ce, P, S	100
B	1000

Designations (3)

Materials numbers (EN 10027)



Pos. 2 and 3

Ordinary grade steels 00...90

High quality grade

- 10 – spec. phyc. prop. steels
- 11 – construction and machine construction steell
- 12 – machine contruct. steels
- 13 – spec. constr. and ja machine constr. steels

High quality 01...91 – structural steels

- 02...92 – non heat treatable structural steels
- 07...97 – high P- ja S-cont. steels

Tool steels 20...29

Special steels 40...49
(stainless and heat resistant. etc.)

Pos. 4 ja 5

Order no. in class

Structural steels (1)

Non-alloy structural steels (C = 0,2...0,65%)

- ordinary (quality) steels
- quality steels *C15E (max S), C15R (S range)*
- high quality steels (S, P ≤ 0,025%)

- Free cutting steels (C = 0,12...0,4%; → 0,2% S) – *10S20, 35S20*
- Cast steels (C = 0,15...0,55%) – *GE250, G28Mn6*

Structural steels (2)

Alloy structural steels (C = 0,2...0,7%, wear resistant steels 0,9...1,3%)

- low alloy steels (all. elem. → 2,5%)
  - structural steels
  - cold forming steels
  - spring steels (C = 0,5...0,7%, Si = 1...2%)
  - ball bearing steels (C ≈ 1%, Cr = 0,5...0,6%)
- medium alloy steels (all. elem. 2,5...5%)
  - cementizing steels
  - quenching and tempering steels
  - nitriding steels
- high alloy steels (leg. el. > 5%) – steels with specific properties
  - corrosion resistant steels
  - high temperature strength steels
  - wear resistant steels

Structural steels (3)

Low alloy steels (1)

Steels for structural construction

Low alloy carbon steels   C≤0,22%; 1...2% Si, Mn

Requirements:

- Cold brittleness: low T_{BCT}, T_{50}
  high toughness (↑ impact energy KU, KV)
- Weldability

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

CE≤0,40% - satisfactory weldability

CE≥0,40% - special means: preheating, low annealing.

Alloying principles: ↓P,S →↓ T_{BCT}

Simultaneous alloying with V,N→T_{BCT} -80°C

Structural steels (4)

Low alloy steels (2)

Cold forming steels

Requirements

- low yield strength ratio ($R_{p0,2}/R_m$ = 0,5...0,65)
- high plasticity (A ≥ 40%)

Principles of alloying:

C and Si%↑ $R_{p0,2}$ →↓ formability; Mn% ↑ R_m, $R_{p0,2}$≈ → good formability

Preferred:

- rimmed steels (Si ≈ 0%)
- dual phase steels (F + 20...30% M or B)

(C = 0,06...0,12%, partial-hardening → $R_{p0,2}/R_m$ = 0,5) → good deep drawability at 10% degree of deformation $R_{p0,2}/R_m$ = 0,8...0,9

- Ballon steels
- Pressure vessel steels
- Seamless pipes
- Welded pipes

Structural steels (5)

Low alloy steels (3)

Spring steels

high R_e, σ_R, modulus of elasticity E

C = 0,5...0,7%

Mn-steels (1...2% Mn)

Si-steels (2...3% Si)

Cr-V-steels

TT: Hardening + mid. temp. (300...400°C) → Trostite structure

Ball bearing steels

High hardness (≥ 62 HRC)

C ≈ 1%; Cr = 0,6...1,5% – *105 Cr6*

Ball races (63...64 HRC), balls (61...62 HRC)

Structural steels (6)

Medium alloy steels (1)

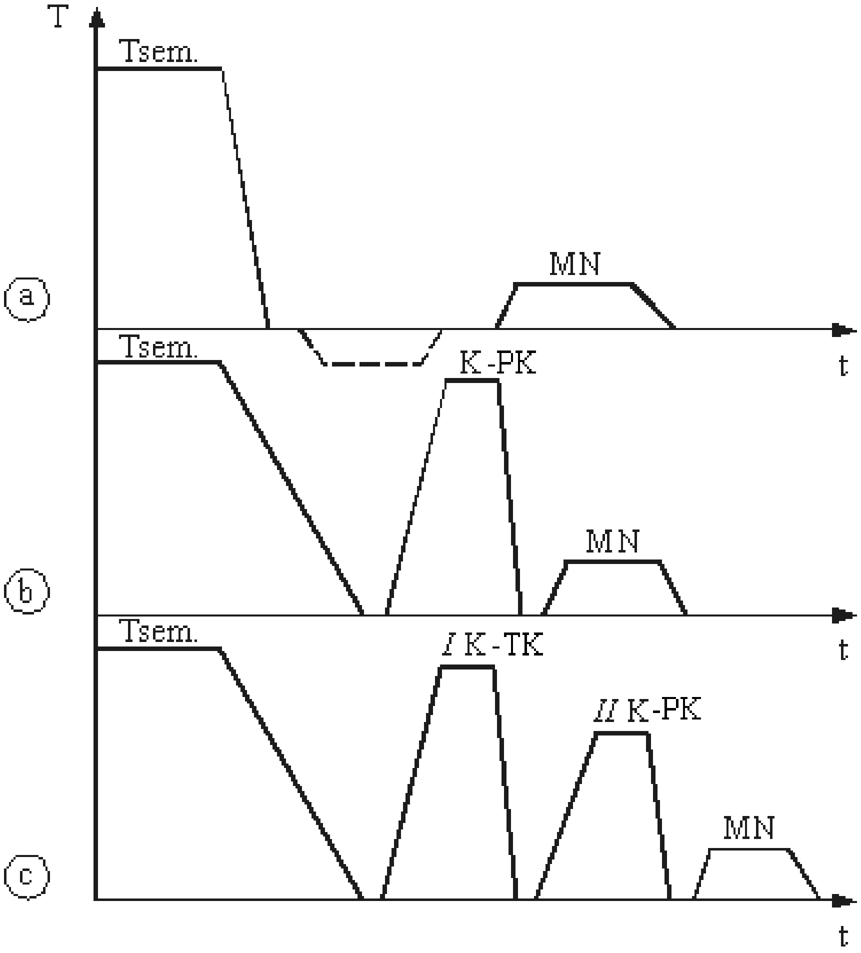
Cementizing (case hardening) **steels** (0,1...0,25% C)

- Cr-steels
- Cr-Mn-steels
- Cr-Ni-steels
- B-steels

HT: T_{cem} + hard. + low. temp.

Surface (C→0,8) – 58...62 HRC

Core (C = 0,1...0,25) – 30...42 HRC



Structural steels (7)

Medium alloy steels (2)

Quenching and tempering steels

Requirements:

- Reliability (↑ R_m, $R_{p0,2}$; acceptable KU and T_{BCT})
- High hardenability (D_{50}, D_{95}, T_{50})

Principles pf alloying:

- Alloying →↑hardenability (↓M_a, M_l) (all exc. Al and Co)
- At solution in F, ↑ R_m and T_{BCT}, alloying degree as low as possible (for ↑D_{50})

Structural steels (8)

Medium alloy steels (3)

Quenching and tempering steels (0,3...0,5% C; 3...5% all.elem.)

	D_{95}, mm	T_{50}, °C
I gr – non-alloy steels (carbon steels)	10...15	20
II gr – Si-Mn/Cr-steels (~1%)	20	-30...-50
III gr – Mn-Cr-steels	25	-60
IV gr – Ni-Mo-steels	40	-80
V gr – Ni-refractory. (W, Mo, V jt.)	100	-100

$R_m \rightarrow 1200$ N/mm^2; $R_{p0,2} \rightarrow$ 1100 N/mm^2; A = 10...12%; KU→40J

Structural steels (9)

Medium alloy steels (4)

Nitriding steels (C-, all. elem. – same as in hard. and temp. steels)

T_{nitr} 500...600°C (differently from cem.)

All. elem. Cr, Mo, Al + N → CrN, MoN, AlN

Properties:

Hardness: surface – alloy steels 950...1150 HV,
non-alloy steels (carbon steels) 400...500 HV
Core 250...300 HB

High fatigue strength (by comp. stresses induced nitrides)

Structural steels (10)

High alloy steels (1)

Corrosion resistant steels (1)

- Cr-steels, C – min (0,08...0,2%)
  0,1...0,4% – for hardenability
  Cr = 13, 17 or 27%

C↑→corrosion resistance ↓, C < 0,1 %C – ferritic steels

For hardness/ wear resiatance → 0,1...0,4 %C – martensitic steels

Structural steels (11)

High alloy steels (2)

- Cr-Ni steels $C \leq 0{,}12\%$
  18% Cr, 10...12% Ni, Ti/Nb ≤ 1%
  $R_m = 500...600\ N/mm^2$
  $R_{p0,2} = 200...250\ N/mm^2$

Intergranular corrosion (at t°. 500...600 °C):

C↑→corr. resist, ↓, especially in welds → Cr_3C_2 → Cr % reduction in A.

To avoid:

→ Ti, Nb (0,1...0,2%)

→ C↓ (<0,03%)

Structural steels (12)

High alloy steels (3)

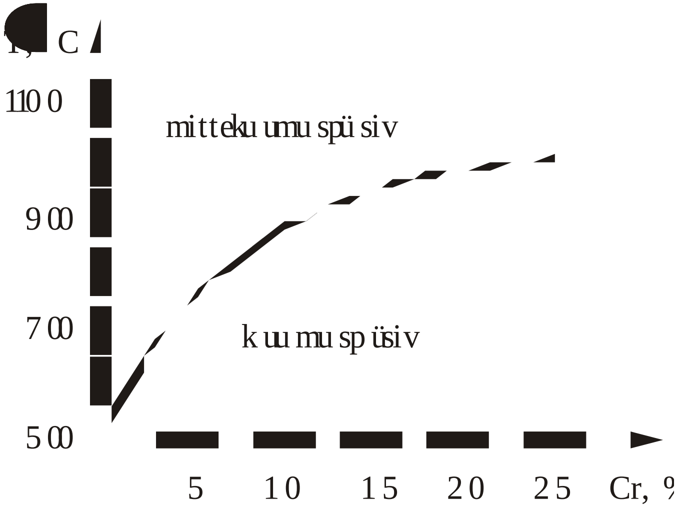
High temperature strength steels

High temperature strength = heat resiatance + high temp. strength

Heat resistance = oxidation resistance

High temp. strength: endurance limit σ_t^T

creep strength $\sigma_{\varepsilon/t}^T$



350...500°C – boiler steels

0,1...0,15% C, 0,5...1% Mo, W või V

0,5...1% Cr (pearlite steels)

2...6% Cr (martensite steels)

- silchrome

0,5...0,6% C, 1,5...3% Si, 5...15% Cr

600...700°C – austenitic steels

13...25% Cr; 14...20% Ni

13...25% Cr; →37% Ni + Al, W, Nb, Ti, Mo

> 700°C - Ni- ja Co-alloys (superalloys)

Structural steels (13)

High alloy steels (4)

Wear resistant steels

Requirements:

High surface hardness

Principles of alloying:

- – through alloying (uneffective – 2...3% /Ø100mm)
- – surface alloying

- Non-alloy- and alloy steels (Cr, Mn, W jt.)
- Cementizing steels
- Mn-steels (Hadfield steel) (1,1...1,3% C, 12...13% Mn)

HT: H (1050...1100°C) → A-structure

R_m=800...1000, $R_{p0,2}$=250...350 N/mm^2, A = 40...50%, 180...220 HB

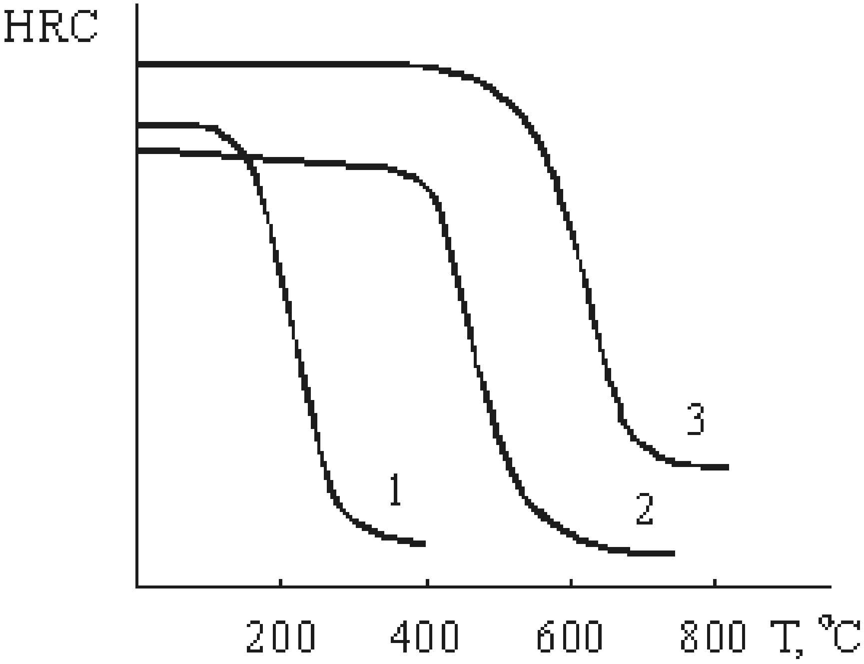
In cold worked conditions → 50...55 HRC – self hardening

Tool steels (1)

Requirements:

- hardness and wear resistance
- strength and toughness
- heat resistance

- Non-alloy tool steels
  (C = 0,7...1,3%)
- Alloy steels
  (C = 0,4...1,6%)
  - non-heat resistant (→200°C)
  - semi heat resistant (→300...500°C)
    - coldwork tool steels
    - hot work tool steels
  - Heat resistant steels (→500...750°C)
    - Carbide induced tempering hardness,
    - Intermetallics induced tempering hardness



Tool steels (2)

Non heat resistant steels (200...250°C)

- non-alloy tool steels (0,7...1,2% C)
- low alloy steels (Cr, W, Mn)

Semi heat resistant steels (300...500°C)

- Cold work tool steels (150...200°C)

Cr-steels (1,2...2,3% C; 12% Cr + Mo, V)

Structure: M + 13...20% carbides

C = 0,6...0,7 – cutting- ja impact tools

- Hot work tool steels

Requirements:

- high temperature strength,
- heat resistance ja thermal resistance
- high hardenability and not prone to tempering brittleness
- low adhesion

Steels 0,5...0,6% C → good toughness

1,5...2% Ni, Mo → high hardenability

Tool steels (3)

<u>Heat resistant steels</u> (500...750°C)

- Steels with carbide induced tempering hardness (500...650°C)

Alloying elements: W (18 or 9%) + Mo, V, Co

- HS-18-0-1
- HS-6-5-2-5 (P6M5K5)

HT: H (1200...1300°C); 3x T (570...650°C) →↓ A_{rest} ;
→ 64...65 HRC

- Steels with intermetallics induced tempering hardness (650...750°C)

Alloying elements: Co, W, Mo → Co_7W_6; $(Co,Fe)_7W_6$ etc.

(0,1...0,3% C, 20...25% Co, 11...20% W, ca 7% Mo)

HT: Hard. (1200...1300°C) → 68 HRC; T (700...720°C) → 60 HRC

Special steels ja -alloys (1)

Magnetic steels

- Soft magnetic materials
  - pure Fe (C < 0,05%)
  - electrotechnical (1...4% Si)
- Hard magnetic materials
  - High C-content Non-alloy tool steels (1,1...1,3% C)
  - Cr-steels (*ca* 1% C; 1,5...3% Cr)
  - Co-steels (*ca* 1% C; 1,5...3% Cr; 5...15% Co)
  - Fe-Ni-Al-alloys (*alniko*) (11...14% Al; 22...34% Ni)

Special steels ja -alloys (2)

Cryogenic steels

Requirements:

- low transition temperature T_{BCT}

Steels for low temperature applications

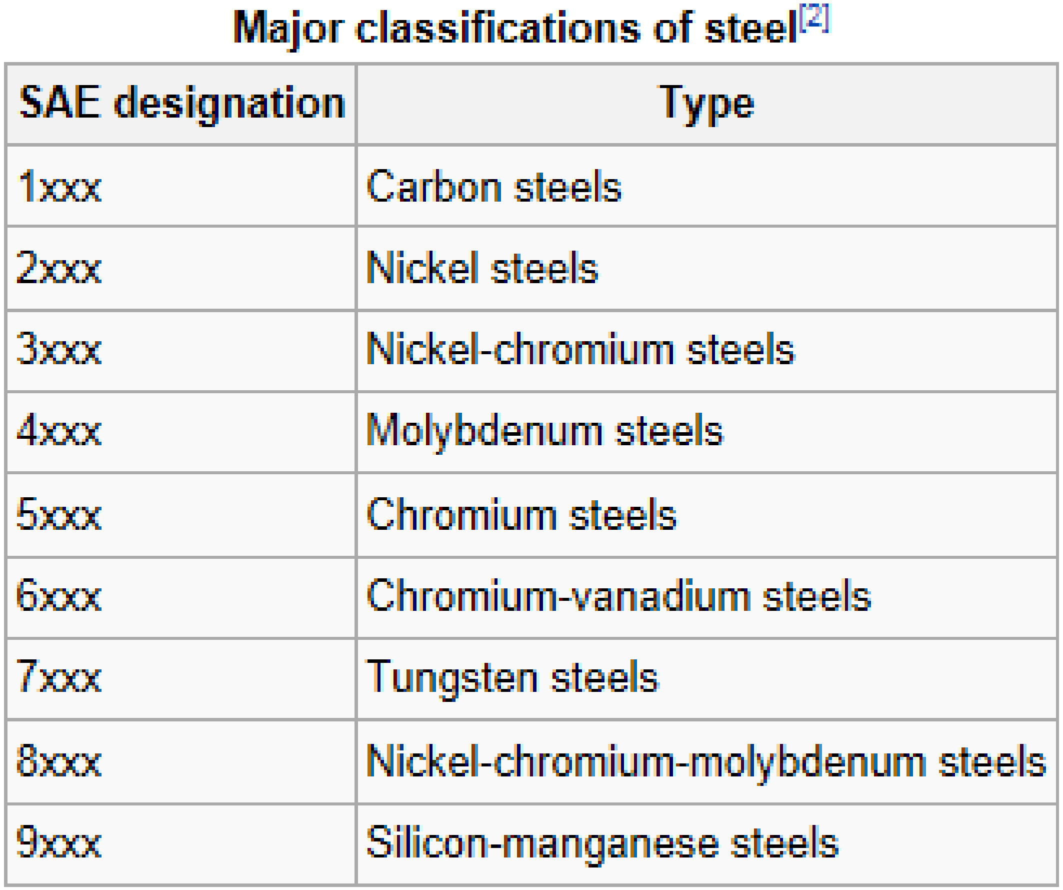
- ≤ –60°C (non-alloy- ja low alloy steel)
- ≤ –100°C – low C-content Ni-steels – 2...5% Ni + Cr, V, Ti
- ≤ –190°C (liquid N_2) – austenitic stainless steels)
- below –190°C (liquid H_2, O_2) – high alloy corrosion resistant steels – Cr > 10%; Ni > 20%

- All of these steels are alloys of Fe and C
  - Plain carbon steels (less than 2% carbon and negligible amounts of other residual elements)
    - Low Carbon (less than 0.3% carbon)
    - Med Carbon (0.3% to 0.6%)
    - High Carbon (0.6% to 0.95%)
  - Low Alloy Steel
  - High Alloy Steel
  - Stainless Steels (Corrosion-Resistant Steels) – contain at least 10.5% Chromium

AISI - SAE Classification System AISI XXXX

American Iron and Steel Institute (AISI)

- **classifies alloys by chemistry**
- **4 digit number**
  - 1st number is the major alloying element
  - 2nd number designates the subgroup alloying element OR the relative percent of primary alloying element.
  - last two numbers approximate amount of carbon (expresses in 0.01%)



Major classifications of steel[2]

SAE designation	Type
1xxx	Carbon steels
2xxx	Nickel steels
3xxx	Nickel-chromium steels
4xxx	Molybdenum steels
5xxx	Chromium steels
6xxx	Chromium-vanadium steels
7xxx	Tungsten steels
8xxx	Nickel-chromium-molybdenum steels
9xxx	Silicon-manganese steels

Examples:

2350

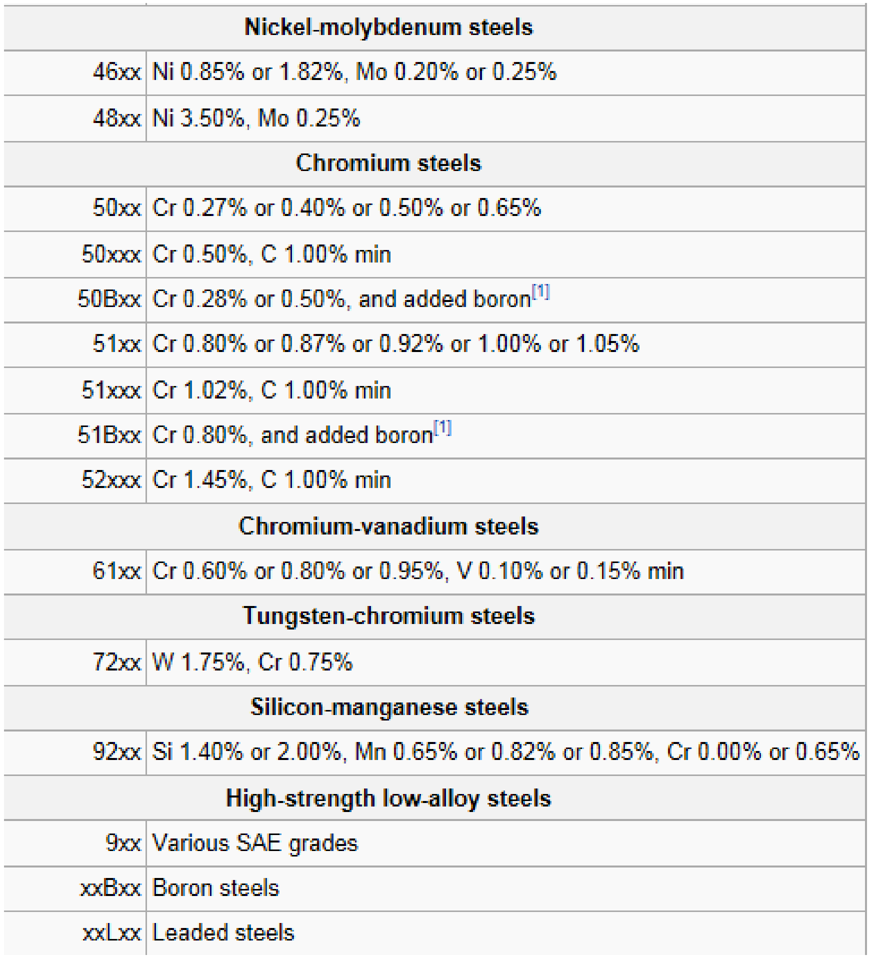
2550

4140

1060

Common Carbon and Alloy Steels:

SAE designation	Type
Carbon steels	
10xx	Plain carbon (Mn 1.00% max)
11xx	Resulfurized
12xx	Resulfurized and rephosphorized
15xx	Plain carbon (Mn 1.00% to 1.65%)
Manganese steels	
13xx	Mn 1.75%
Nickel steels	
23xx	Ni 3.50%
25xx	Ni 5.00%
Nickel-chromium steels	
31xx	Ni 1.25%, Cr 0.65% or 0.80%
32xx	Ni 1.25%, Cr 1.07%
33xx	Ni 3.50%, Cr 1.50% or 1.57%
34xx	Ni 3.00%, Cr 0.77%
Molybdenum steels	
40xx	Mo 0.20% or 0.25% or 0.25% Mo & 0.042 S[1]
44xx	Mo 0.40% or 0.52%
Chromium-molybdenum (Chromoly) steels	
41xx	Cr 0.50% or 0.80% or 0.95%, Mo 0.12% or 0.20% or 0.25% or 0.30%
Nickel-chromium-molybdenum steels	
43xx	Ni 1.82%, Cr 0.50% to 0.80%, Mo 0.25%
43BVxx	Ni 1.82%, Cr 0.50%, Mo 0.12% or 0.35%, V 0.03% min
47xx	Ni 1.05%, Cr 0.45%, Mo 0.20% or 0.35%
81xx	Ni 0.30%, Cr 0.40%, Mo 0.12%
81Bxx	Ni 0.30%, Cr 0.45%, Mo 0.12%, and added boron[1]
86xx	Ni 0.55%, Cr 0.50%, Mo 0.20%
87xx	Ni 0.55%, Cr 0.50%, Mo 0.25%
88xx	Ni 0.55%, Cr 0.50%, Mo 0.35%
93xx	Ni 3.25%, Cr 1.20%, Mo 0.12%
94xx	Ni 0.45%, Cr 0.40%, Mo 0.12%
97xx	Ni 0.55%, Cr 0.20%, Mo 0.20%
98xx	Ni 1.00%, Cr 0.80%, Mo 0.25%



Nickel-molybdenum steels	
46xx	Ni 0.85% or 1.82%, Mo 0.20% or 0.25%
48xx	Ni 3.50%, Mo 0.25%
Chromium steels	
50xx	Cr 0.27% or 0.40% or 0.50% or 0.65%
50xxx	Cr 0.50%, C 1.00% min
50Bxx	Cr 0.28% or 0.50%, and added boron[1]
51xx	Cr 0.80% or 0.87% or 0.92% or 1.00% or 1.05%
51xxx	Cr 1.02%, C 1.00% min
51Bxx	Cr 0.80%, and added boron[1]
52xxx	Cr 1.45%, C 1.00% min
Chromium-vanadium steels	
61xx	Cr 0.60% or 0.80% or 0.95%, V 0.10% or 0.15% min
Tungsten-chromium steels	
72xx	W 1.75%, Cr 0.75%
Silicon-manganese steels	
92xx	Si 1.40% or 2.00%, Mn 0.65% or 0.82% or 0.85%, Cr 0.00% or 0.65%
High-strength low-alloy steels	
9xx	Various SAE grades
xxBxx	Boron steels
xxLxx	Leaded steels

AISI - SAE Classification System

- letter prefix to designate the process used to produce the steel
  - E = electric furnace
  - X = indicates permissible variations
- If a letter is inserted between the 2nd and 3rd number
  - B = boron has been added
  - L = lead has been added
- Letter suffix
  - H = when hardenability is a major requirement
- Other designation organizations
  - ASTM and MIL

AISI/SAE most common, also have Unified Numbering System (UNS) and ASTM

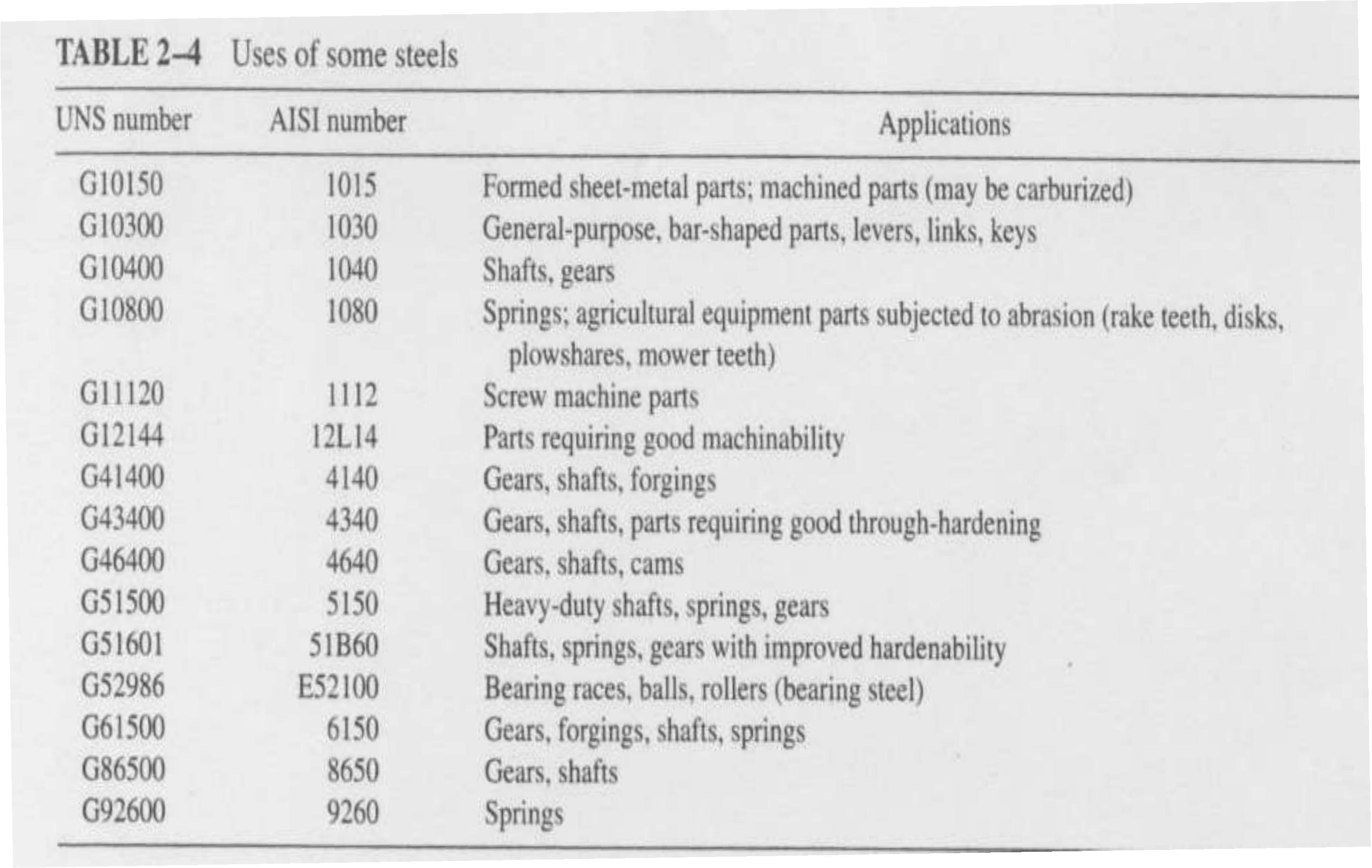


TABLE 2–4 Uses of some steels

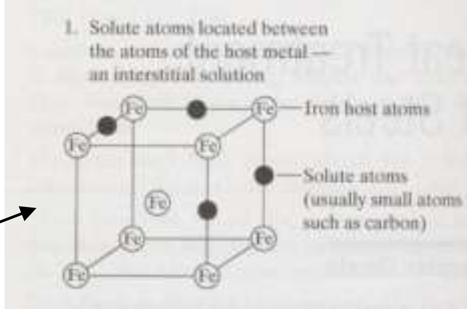
UNS number	AISI number	Applications
G10150	1015	Formed sheet-metal parts; machined parts (may be carburized)
G10300	1030	General-purpose, bar-shaped parts, levers, links, keys
G10400	1040	Shafts, gears
G10800	1080	Springs; agricultural equipment parts subjected to abrasion (rake teeth, disks, plowshares, mower teeth)
G11120	1112	Screw machine parts
G12144	12L14	Parts requiring good machinability
G41400	4140	Gears, shafts, forgings
G43400	4340	Gears, shafts, parts requiring good through-hardening
G46400	4640	Gears, shafts, cams
G51500	5150	Heavy-duty shafts, springs, gears
G51601	51B60	Shafts, springs, gears with improved hardenability
G52986	E52100	Bearing races, balls, rollers (bearing steel)
G61500	6150	Gears, forgings, shafts, springs
G86500	8650	Gears, shafts
G92600	9260	Springs

Plain Carbon Steel

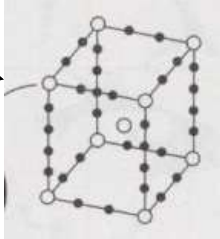
Plain Carbon Steel

- **Lowest cost**
- **Should be considered first in most application**
- **3 Classifications**
  - Low Carbon (less than 0.3% carbon)
  - Med Carbon (0.3% to 0.6%)
  - High Carbon (0.6% to 0.95%)

Plain Carbon Steel



- Again, alloy of iron and carbon with carbon the major strengthening element via solid solution strengthening.
- If carbon level high enough (greater than 0.6%) can be quench hardened (aka: dispersion hardening, through hardened, heat treated, austenized and quenched, etc..).



- Can come in HRS and CRS options
- The most common CRS are 1006 through 1050 and 1112, 1117 and other free machining steels

Plain Carbon Steel

1. Low Carbon (less than 0.3% carbon)

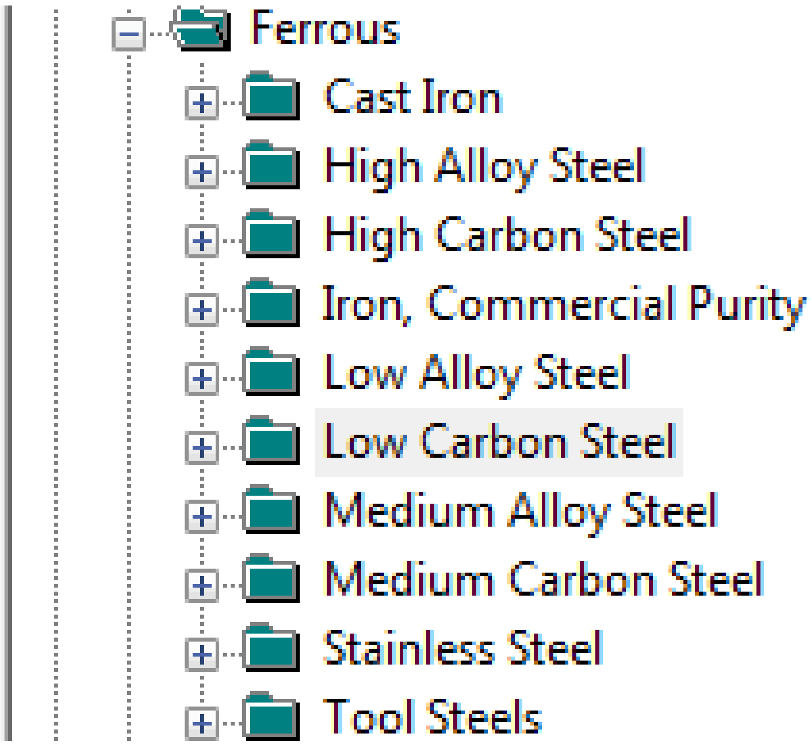
- Low strength, good formability
    - If wear is a potential problem, can be carburized (diffusion hardening)
    - Most stampings made from these steels
    - AISI 1008, 1010, 1015, 1018, 1020, 1022, 1025

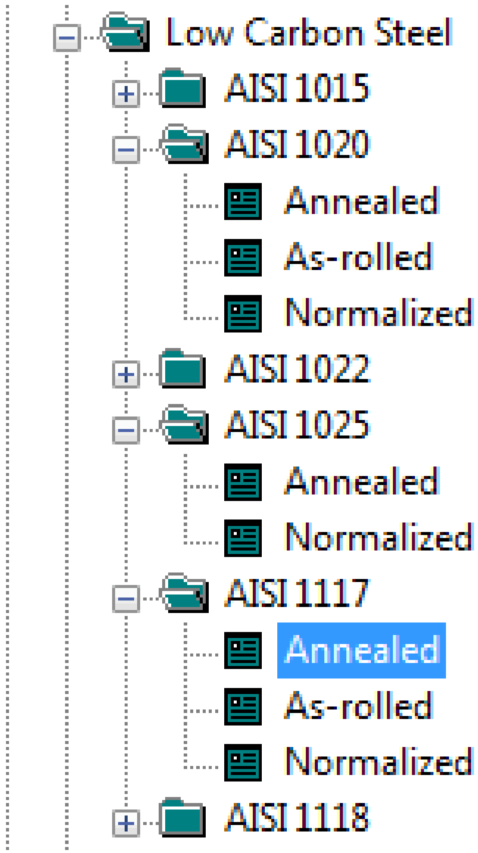
2. Med Carbon (0.3% to 0.6%)

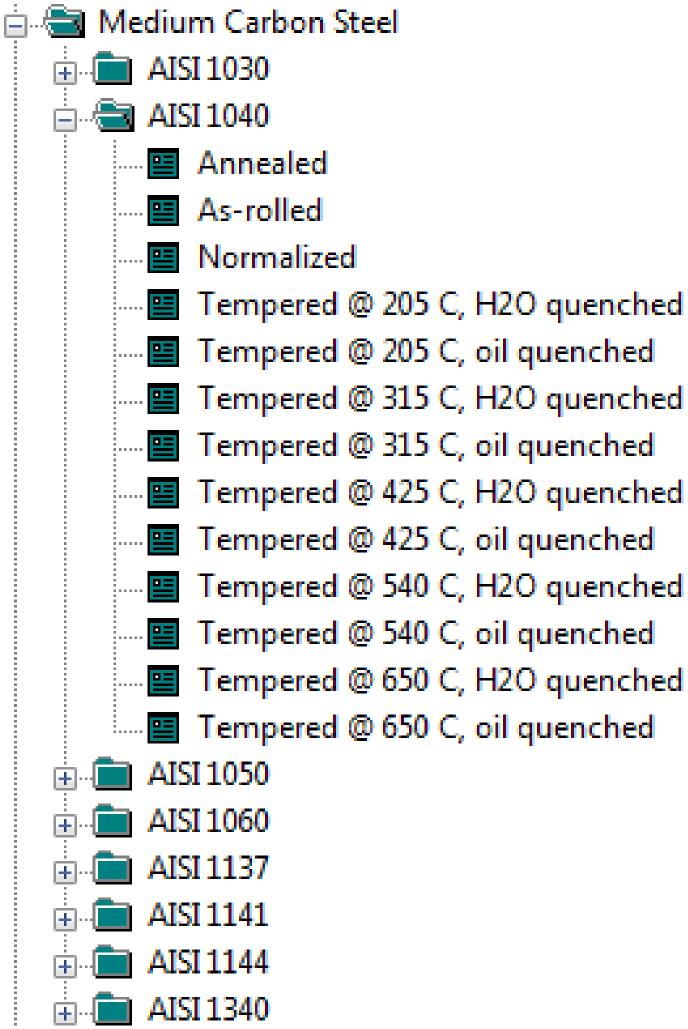
- Have moderate to high strength with fairly good ductility
- Can be used in most machine elements
- AISI 1030, 1040, 1050, 1060*

3. High Carbon (0.6% to 0.95%)

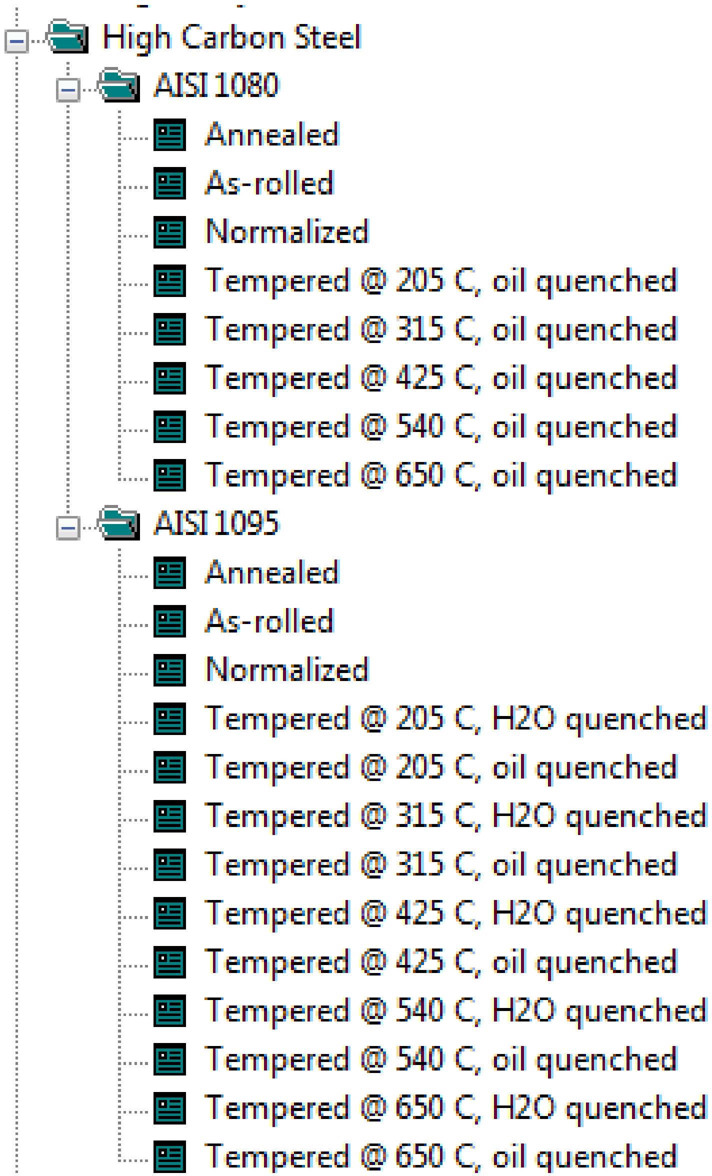
- Have high strength, lower elongation
- Can be quench hardened
- Used in applications where surface subject to abrasion – tools, knives, chisels, ag implements.
- AISI 1080, 1095


Ferrous
Cast Iron
High Alloy Steel
High Carbon Steel
Iron, Commercial Purity
Low Alloy Steel
Low Carbon Steel
Medium Alloy Steel
Medium Carbon Steel
Stainless Steel
Tool Steels


Low Carbon Steel
AISI 1015
AISI 1020
Annealed
As-rolled
Normalized
AISI 1022
AISI 1025
Annealed
Normalized
AISI 1117
Annealed
As-rolled
Normalized
AISI 1118

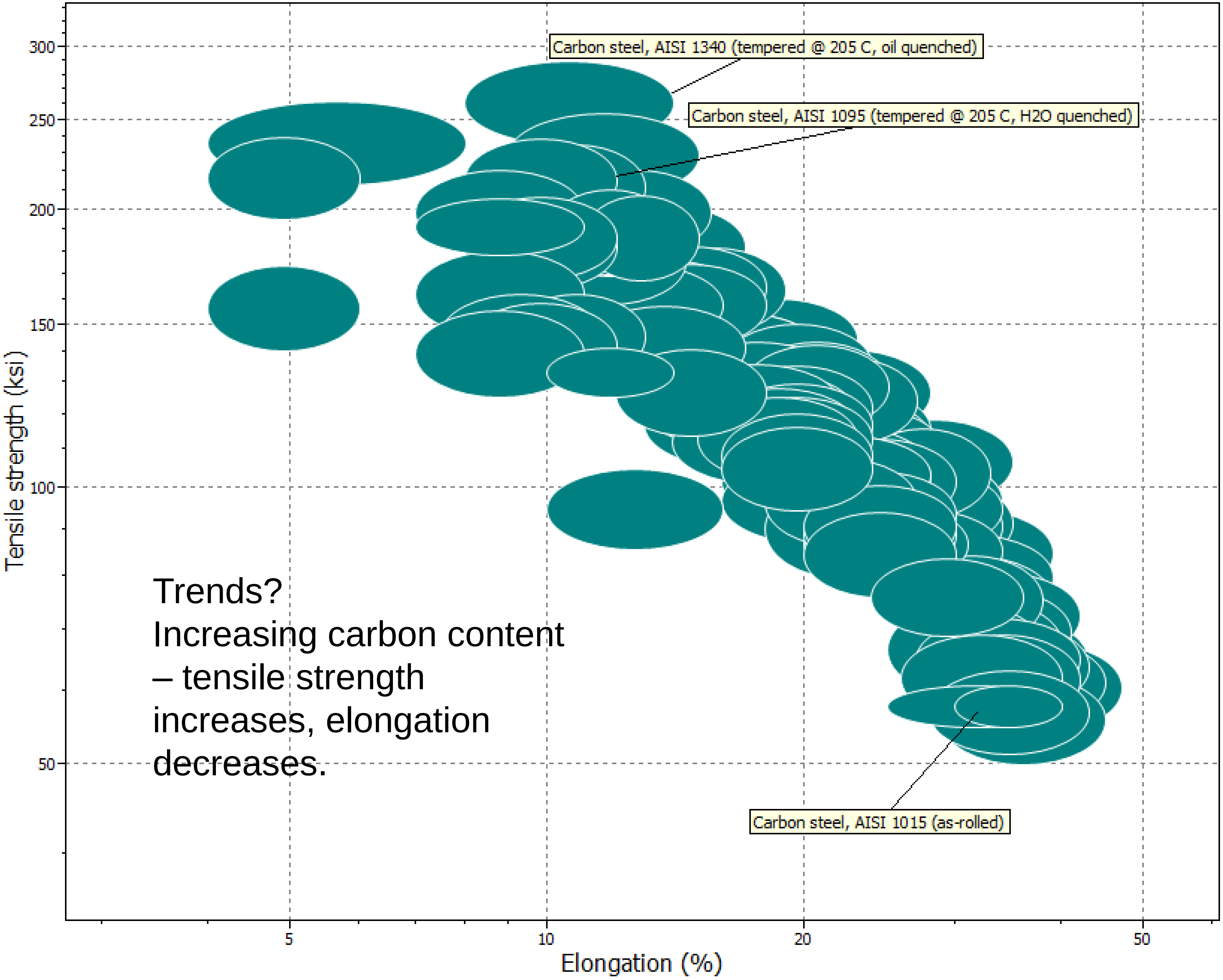


- Medium Carbon Steel
  - AISI 1030
  - AISI 1040
    - Annealed
    - As-rolled
    - Normalized
    - Tempered @ 205 C, H2O quenched
    - Tempered @ 205 C, oil quenched
    - Tempered @ 315 C, H2O quenched
    - Tempered @ 315 C, oil quenched
    - Tempered @ 425 C, H2O quenched
    - Tempered @ 425 C, oil quenched
    - Tempered @ 540 C, H2O quenched
    - Tempered @ 540 C, oil quenched
    - Tempered @ 650 C, H2O quenched
    - Tempered @ 650 C, oil quenched
  - AISI 1050
  - AISI 1060
  - AISI 1137
  - AISI 1141
  - AISI 1144
  - AISI 1340



- High Carbon Steel
  - AISI 1080
    - Annealed
    - As-rolled
    - Normalized
    - Tempered @ 205 C, oil quenched
    - Tempered @ 315 C, oil quenched
    - Tempered @ 425 C, oil quenched
    - Tempered @ 540 C, oil quenched
    - Tempered @ 650 C, oil quenched
  - AISI 1095
    - Annealed
    - As-rolled
    - Normalized
    - Tempered @ 205 C, H2O quenched
    - Tempered @ 205 C, oil quenched
    - Tempered @ 315 C, H2O quenched
    - Tempered @ 315 C, oil quenched
    - Tempered @ 425 C, H2O quenched
    - Tempered @ 425 C, oil quenched
    - Tempered @ 540 C, H2O quenched
    - Tempered @ 540 C, oil quenched
    - Tempered @ 650 C, H2O quenched
    - Tempered @ 650 C, oil quenched

Carbon steels: low, med and hight



Trends?
Increasing carbon content – tensile strength increases, elongation decreases.

Plain Carbon Steel

- **1018**
  - **Low carbon Yield strength 55ksi**
- **1045**
  - **Medium carbon Yield strength 70ksi**
- **A36**
  - **Low carbon Yield strength 36ksi**
- **12L14**
  - **Low carbon Yield strength 70ksi**
- **1144**
  - **Medium carbon Yield strength 95ksi**

HRS vs. CRS

- HRS
  - AKA hot finishing – ingots or continuous cast shapes rolled in the “HOT” condition to a smaller shape.
  - Since hot, grains recrystallize without material getting harder!
  - Dislocations are annihilated (recall dislocations impede slip motion).

- HRS Characterized by:
  - Extremely ductile (i.e. % elongation 20 to 30%)
  - Moderate strength (Su approx 60 – 75 ksi for 1020)
  - Rough surface finish – black scale left on surface.

HRS vs. CRS

- CRS
  - AKA cold finishing – coil of HRS rolled through a series of rolling mills AT ROOM TEMPERATURE.
  - Since rolled at room temperature, get crystal defects called dislocations which impede motion via slip!
  - AKA work hardening
  - Limit to how much you can work harden before too brittle.
  - How reverse? Can recrystallize by annealing.

- CRS Characterized by:
  - Less ductlie – almost brittle (i.e. % elongation 5 to 10%)
  - High strength (Su approx 120 ksi for 1020)

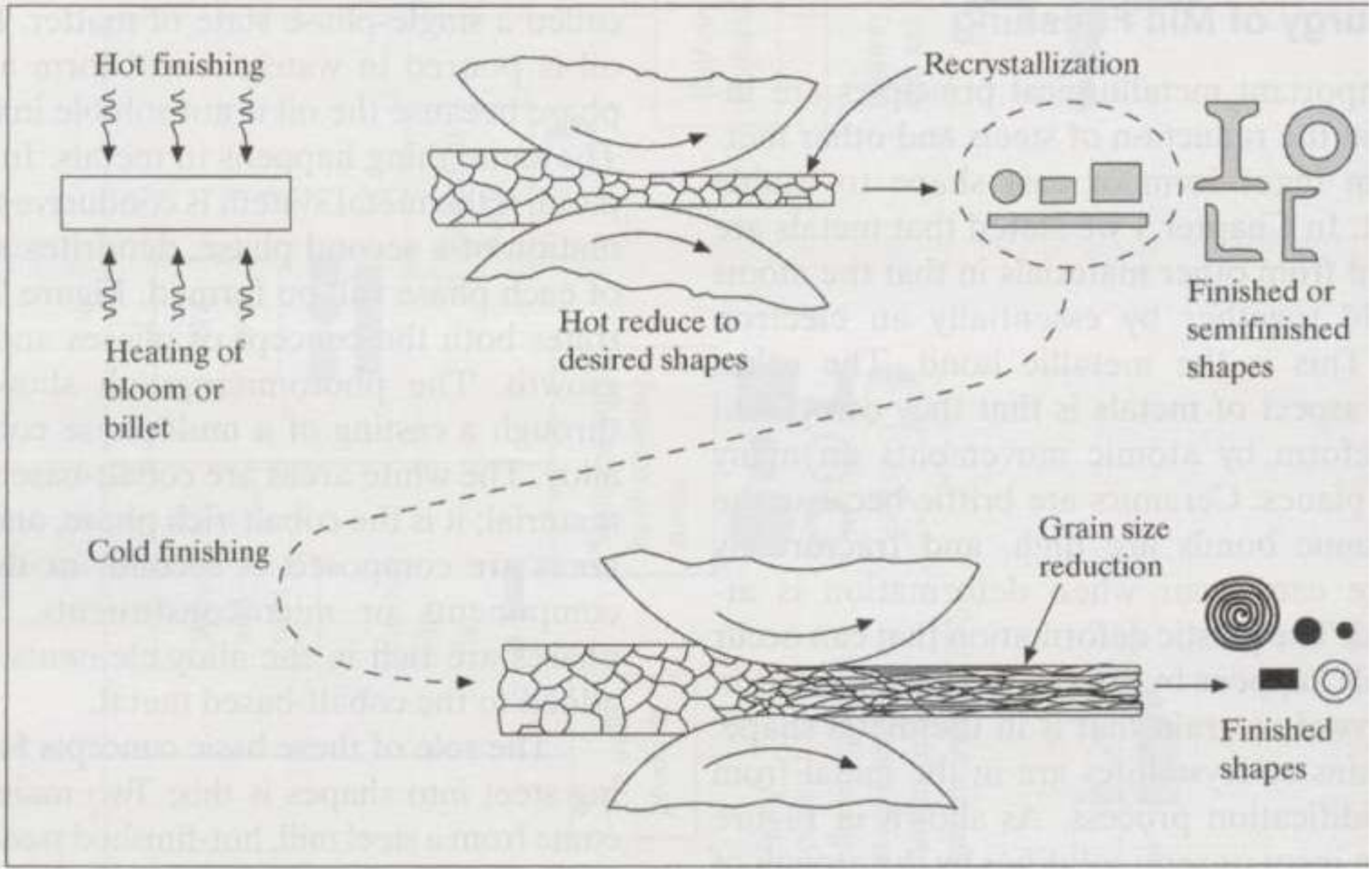
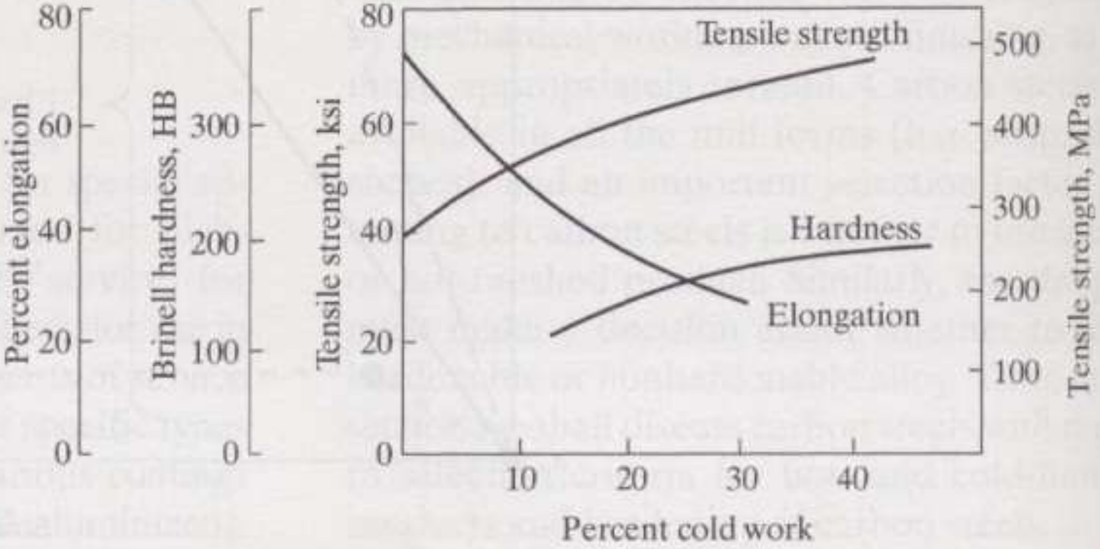

Hot finishing
Recrystallization
Heating of bloom or billet
Hot reduce to desired shapes
Finished or semifinished shapes
Grain size reduction
Cold finishing
Finished shapes

Figure 11–3
Effect of mechanical working on the properties of iron

Source: L. H. Van Vlack, *Elements of Material Science,* Reading, MA: Addison-Wesley Publishing Co., Inc., 1959



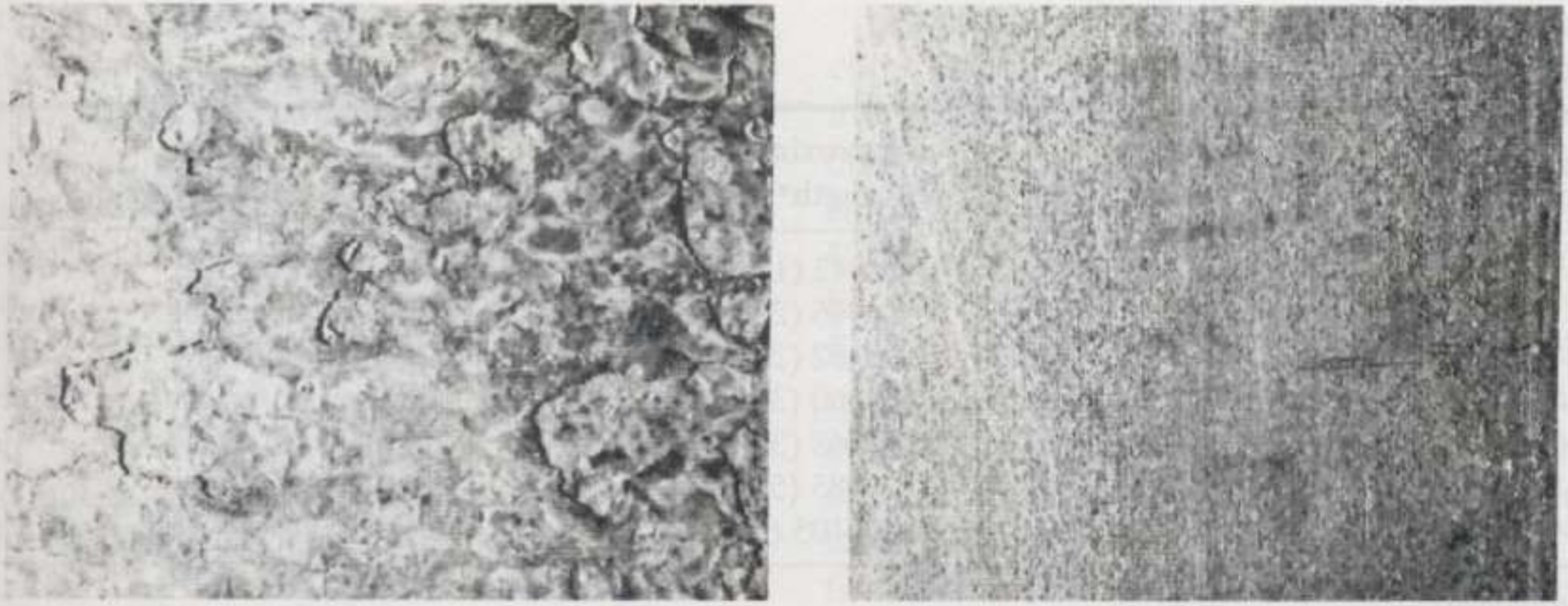

(a)
(b)

Figure 11–5
Surface finish of (a) hot-rolled and (b) cold-rolled 1020 steel plate (×4)

Alloy Steel

- Other elements (besides carbon) can be added to iron to improve mechanical property, manufacturing, or environmental property.
- Example: sulfur, phosphorous, or lead can be added to improve machine ability.
  - Generally want to use for screw machine parts or parts with high production rates!
  - Examples: 11xx, 12xx and 12Lxx

Alloy Steel

- Again, elements added to steel can dissolve in iron (solid solution strengthening):
  - Increase strength, hardenability, toughness, creep, high temp resistance.
- Alloy steels grouped into low, med and high-alloy steels.
  - High-alloy steels would be the stainless steel groups.
  - Most alloy steels you’ll use fall under the category of low alloy.

Alloy Steel

- > 1.65%Mn, > 0.60% Si, or >0.60% Cu
- Most common alloy elements:
  - Chromium, nickel, molybdenum, vanadium, tungsten, cobalt, boron, and copper.
- Low alloy: Added in small percents (<5%)
  - increase strength and hardenability
- High alloy: Added in large percents (>20%)
  - i.e. > 10.5% Cr = stainless steel where Cr improves corrosion resistance and stability at high or low temps

Alloying Elements used in Steel

Manganese (Mn)

- **combines with sulfur to prevent brittleness**
- **>1%**
  - **increases hardenability**
- **11% to 14%**
  - **increases hardness**
  - **good ductility**
  - **high strain hardening capacity**
  - **excellent wear resistance**
- ***Ideal for impact resisting tools***

Alloying Elements used in Steel

Sulfur (S)

- Imparts brittleness
- Improves machineability
- Okay if combined with Mn
- Some free-machining steels contain 0.08% to 0.15% S
- Examples of S alloys:
  - 11xx – sulfurized (free-cutting)

Alloying Elements used in Steel

Nickel (Ni)

- **Provides strength, stability and toughness, Examples of Ni alloys:**
  - **30xx – Nickel (0.70%), chromium (0.70%)**
  - **31xx – Nickel (1.25%), chromium (0.60%)**
  - **32xx – Nickel (1.75%), chromium (1.00%)**
  - **33XX – Nickel (3.50%), chromium (1.50%)**

Alloying Elements used in Steel

Chromium (Cr)

- Usually < 2%
- increase hardenability and strength
- Offers corrosion resistance by forming stable oxide surface
- typically used in combination with Ni and Mo
  - 30XX – Nickel (0.70%), chromium (0.70%)
  - 5xxx – chromium alloys
  - 6xxx – chromium-vanadium alloys
  - 41xxx – chromium-molybdenum alloys

Molybdenum (Mo)

- Usually < 0.3%
- increase hardenability and strength
- Mo-carbides help increase creep resistance at elevated temps
  - typical application is hot working tools

Alloying Elements used in Steel

Vanadium (V)

- **Usually 0.03% to 0.25%**
- **increase strength**
  - **without loss of ductility**

Tungsten (W)

- **helps to form stable carbides**
- **increases hot hardness**
  - **used in *tool steels***

Alloying Elements used in Steel

Copper (Cu)

- 0.10% to 0.50%
- increase corrosion resistance
- Reduced surface quality and hot-working ability
- used in low carbon sheet steel and structural steels

Silicon (Si)

- About 2%
- increase strength without loss of ductility
- enhances magnetic properties

Alloying Elements used in Steel

Boron (B)

- for low carbon steels, can drastically increase hardenability
- improves machinablity and cold forming capacity

Aluminum (Al)

- deoxidizer
- 0.95% to 1.30%
- produce Al-nitrides during nitriding

Corrosion Resistant Steel

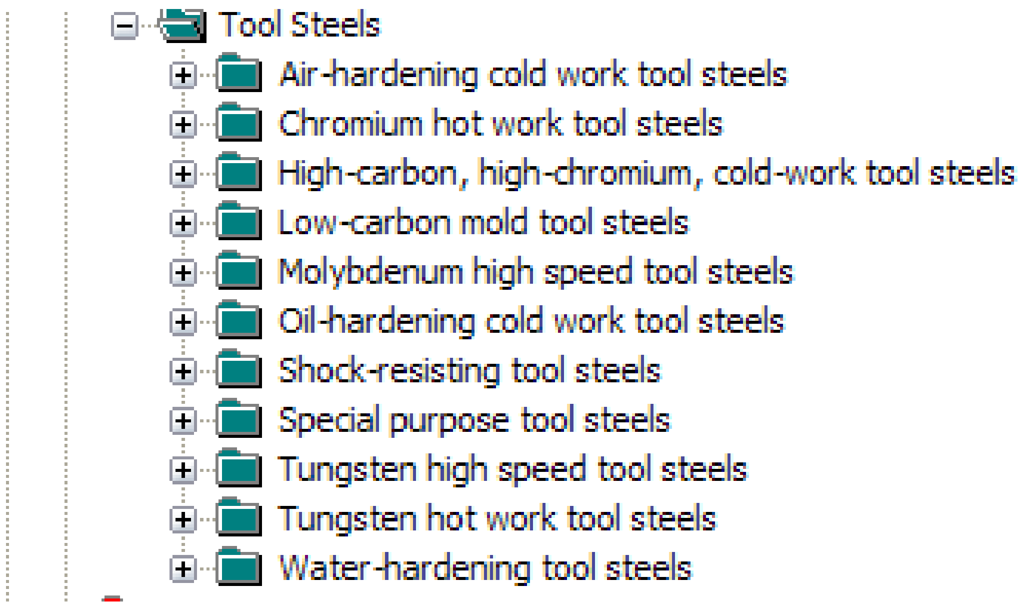
- Stainless Steels (Corrosion-Resistant Steels) – contain at least 10.5% Chromium
  - **trade name**
- **AISI assigns a 3 digit number**
  - **200 and 300 … Austenitic Stainless Steel**
  - **400 … Ferritic or Martensitic Stainless Steel**
  - **500 … Martensitic Stainless Steel**

Tool Steel

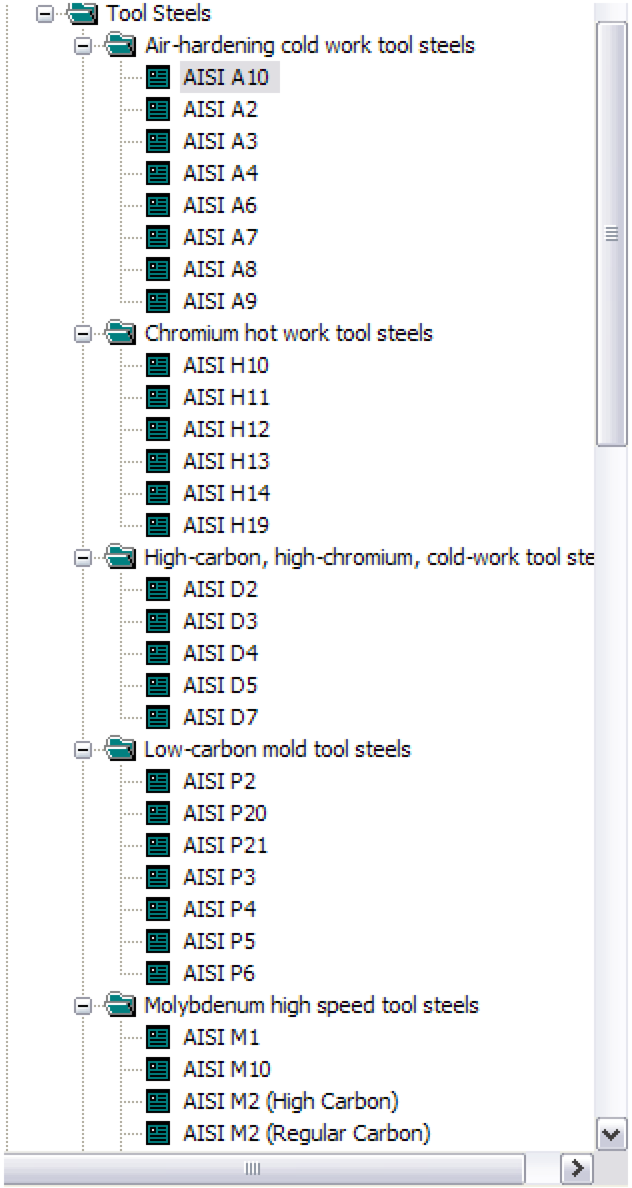
- Refers to a variety of carbon and alloy steels that are particularly well-suited to be made into tools.
- Characteristics include high hardness, resistance to abrasion (excellent wear), an ability to hold a cutting edge, resistance to deformation at elevated temperatures (red-hardness).
- Tool steel are generally used in a heat-treated state.
- High carbon content – very brittle

Tool Steel

AISI-SAE tool steel grades[1]		
Defining property	AISI-SAE grade	Significant characteristics
Water-hardening	W	
Cold-working	O	Oil-hardening
	A	Air-hardening; medium alloy
	D	High carbon; high chromium
Shock resisting	S	
High speed	T	Tungsten base
	M	Molybdenum base
Hot-working	H	H1-H19: chromium base H20-H39: tungsten base H40-H59: molybdenum base
Plastic mold	P	
Special purpose	L	Low alloy
	F	Carbon tungsten



- Tool Steels
  - Air-hardening cold work tool steels
  - Chromium hot work tool steels
  - High-carbon, high-chromium, cold-work tool steels
  - Low-carbon mold tool steels
  - Molybdenum high speed tool steels
  - Oil-hardening cold work tool steels
  - Shock-resisting tool steels
  - Special purpose tool steels
  - Tungsten high speed tool steels
  - Tungsten hot work tool steels
  - Water-hardening tool steels



- Tool Steels
  - Air-hardening cold work tool steels
    - AISI A10
    - AISI A2
    - AISI A3
    - AISI A4
    - AISI A6
    - AISI A7
    - AISI A8
    - AISI A9
  - Chromium hot work tool steels
    - AISI H10
    - AISI H11
    - AISI H12
    - AISI H13
    - AISI H14
    - AISI H19
  - High-carbon, high-chromium, cold-work tool ste
    - AISI D2
    - AISI D3
    - AISI D4
    - AISI D5
    - AISI D7
  - Low-carbon mold tool steels
    - AISI P2
    - AISI P20
    - AISI P21
    - AISI P3
    - AISI P4
    - AISI P5
    - AISI P6
  - Molybdenum high speed tool steels
    - AISI M1
    - AISI M10
    - AISI M2 (High Carbon)
    - AISI M2 (Regular Carbon)

Review CES!

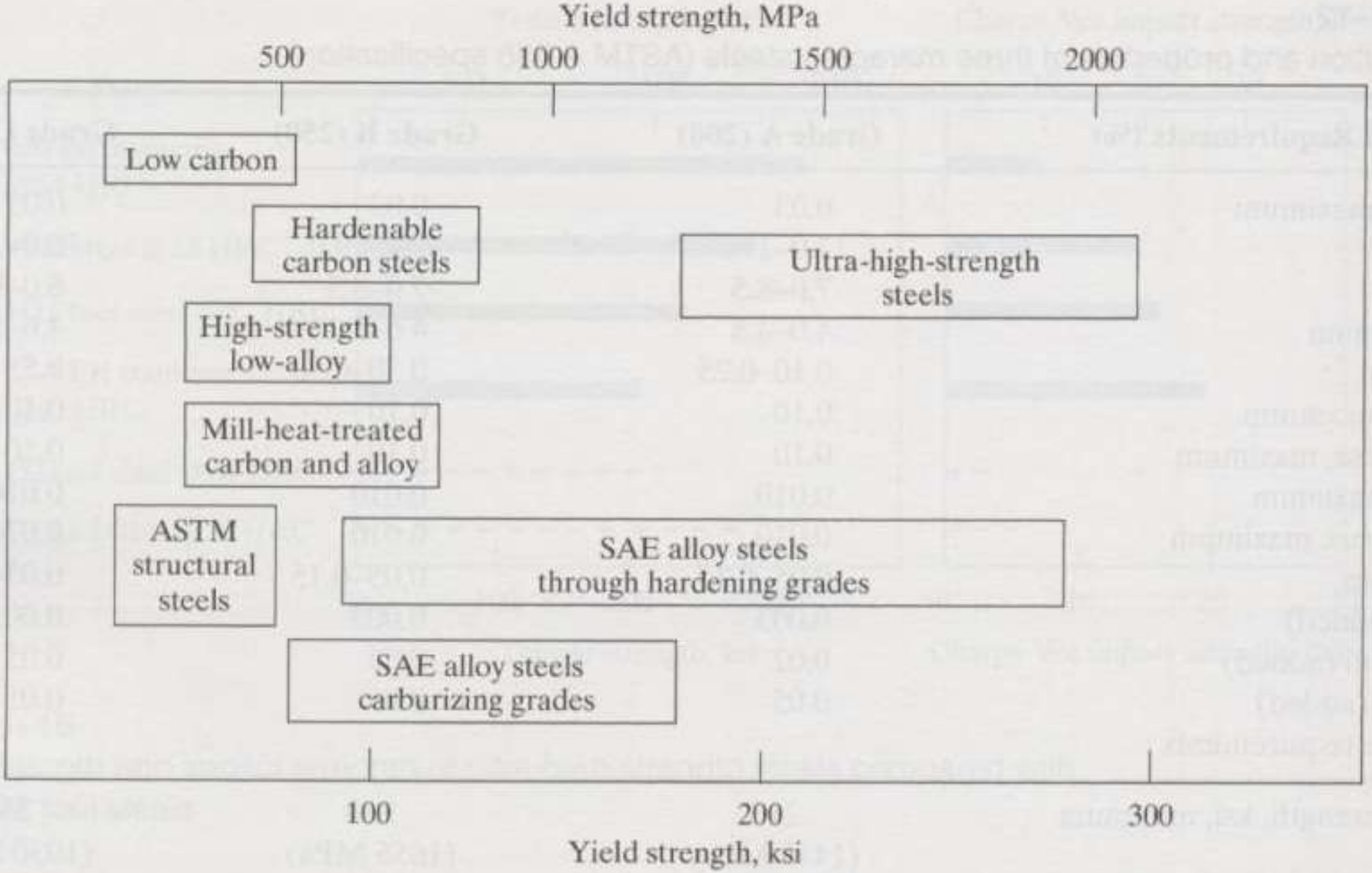
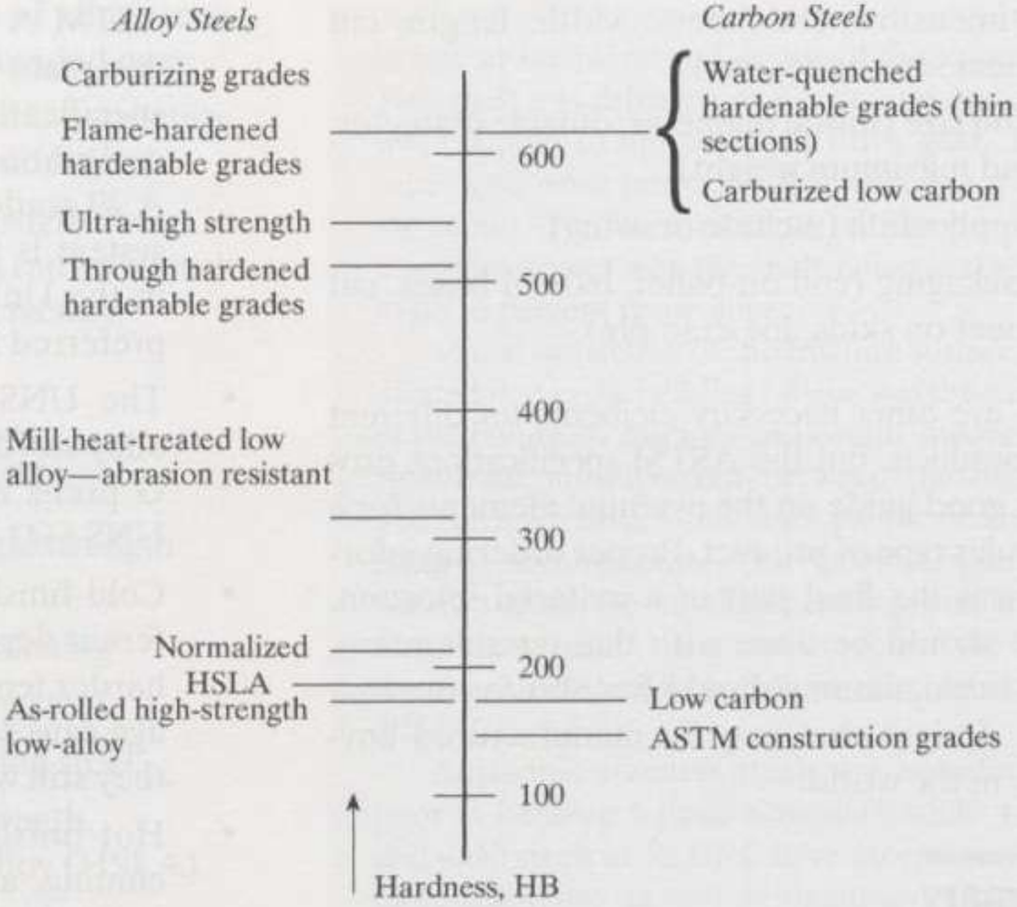


Figure 11–17
Yield strengths possible with various steels

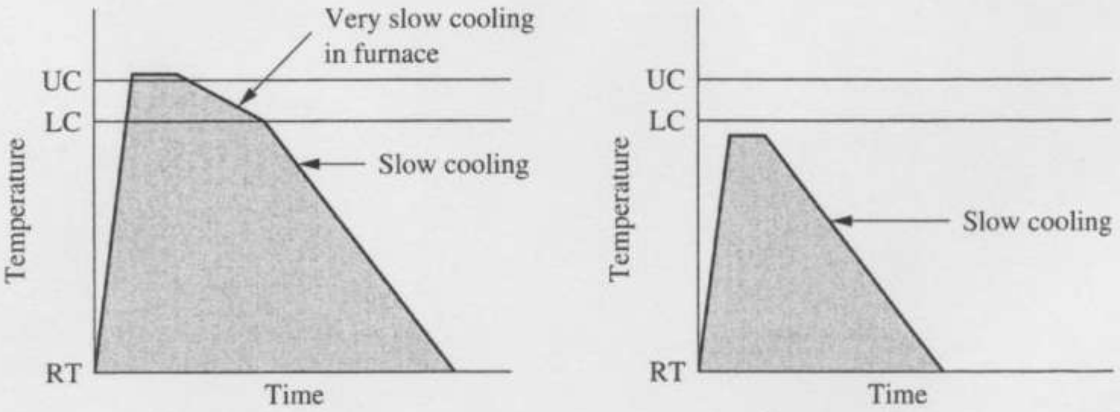
Figure 11–18
Hardness obtainable in various steel systems



Recall, tensile strength approximately 500 X BHN

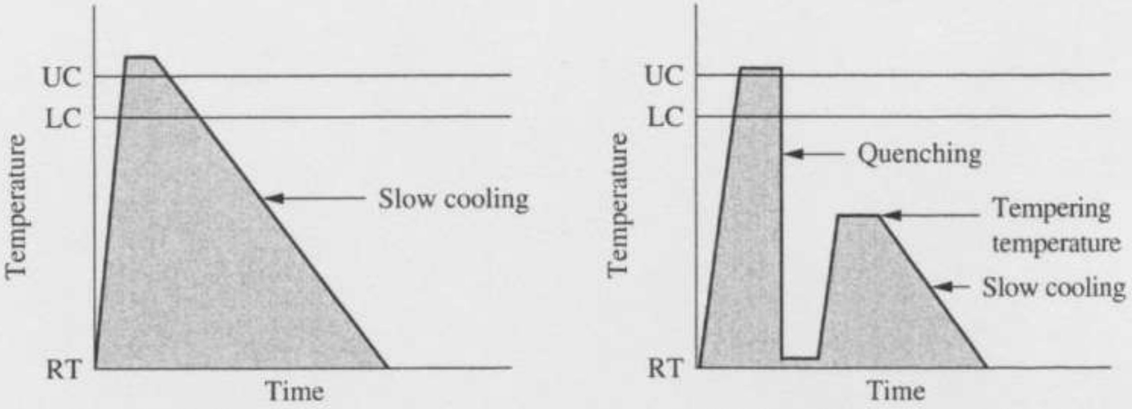
A Quick Review of Heat Treating Processes from Chapter 13:

FIGURE 2–12 Heat treatments for steel



(*a*) Full annealing

(*b*) Stress relief annealing



(*c*) Normalizing

(*d*) Quenching and tempering (through-hardening)

Note:
RT = room temperature
LC = lower critical temperature
UC = upper critical temperature

Know These Basic HT Processes:

- Full Annealing – Heat above the austenite temperature (or UC) until the composition is uniform. Cool very slowly (usually at room temperate outside the oven. Result: a soft, low-strength steel, free of significant internal stresses. Generally done before Cold Forming process.
- Stress relief annealing – Heat slightly below austenitic temperature (or below LC) generally done following welding, machining or cold forming to reduce residual stress.

Know These Basic HT Processes:

- Normalizing: Similar to annealing but at higher temperature. Again, slow cooling. Result: uniform internal structure with somewhat higher strength than the annealing process. Machinability and toughness improved over the as-rolled condition.

Know These Basic HT Processes:

- Through Hardening, Quenching and Tempering (and then slow cooling): – Heat above the austenite temperature (or UC) until the composition is uniform. Cool rapidly (Quench). Result: strong but brittle martensite structure. So temper and slow cool to improve toughness at the expense of strength.

Tensile Strength and Elongation vs Tempering Temperature

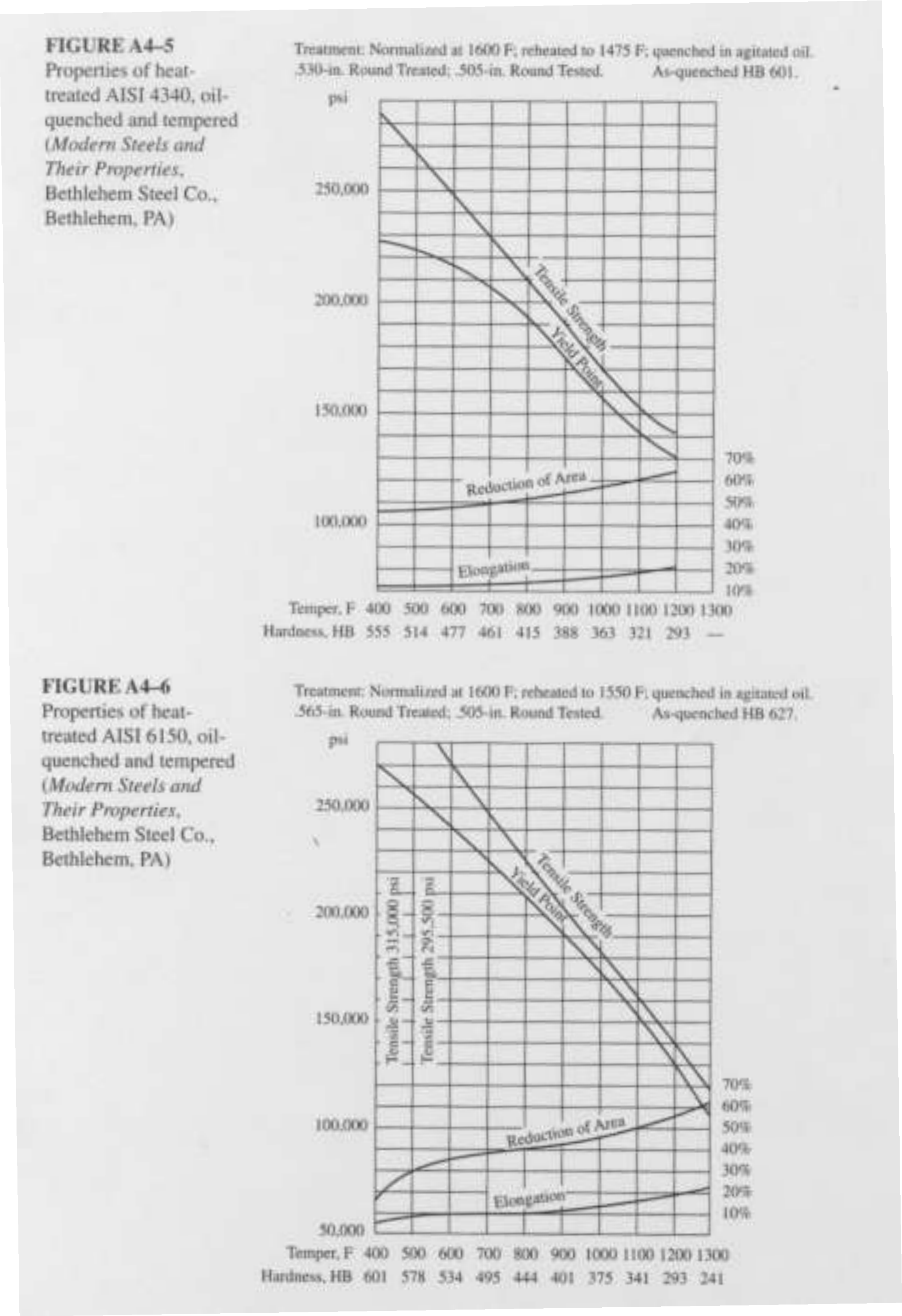


FIGURE A4–5
Properties of heat-treated AISI 4340, oil-quenched and tempered (*Modern Steels and Their Properties*, Bethlehem Steel Co., Bethlehem, PA)

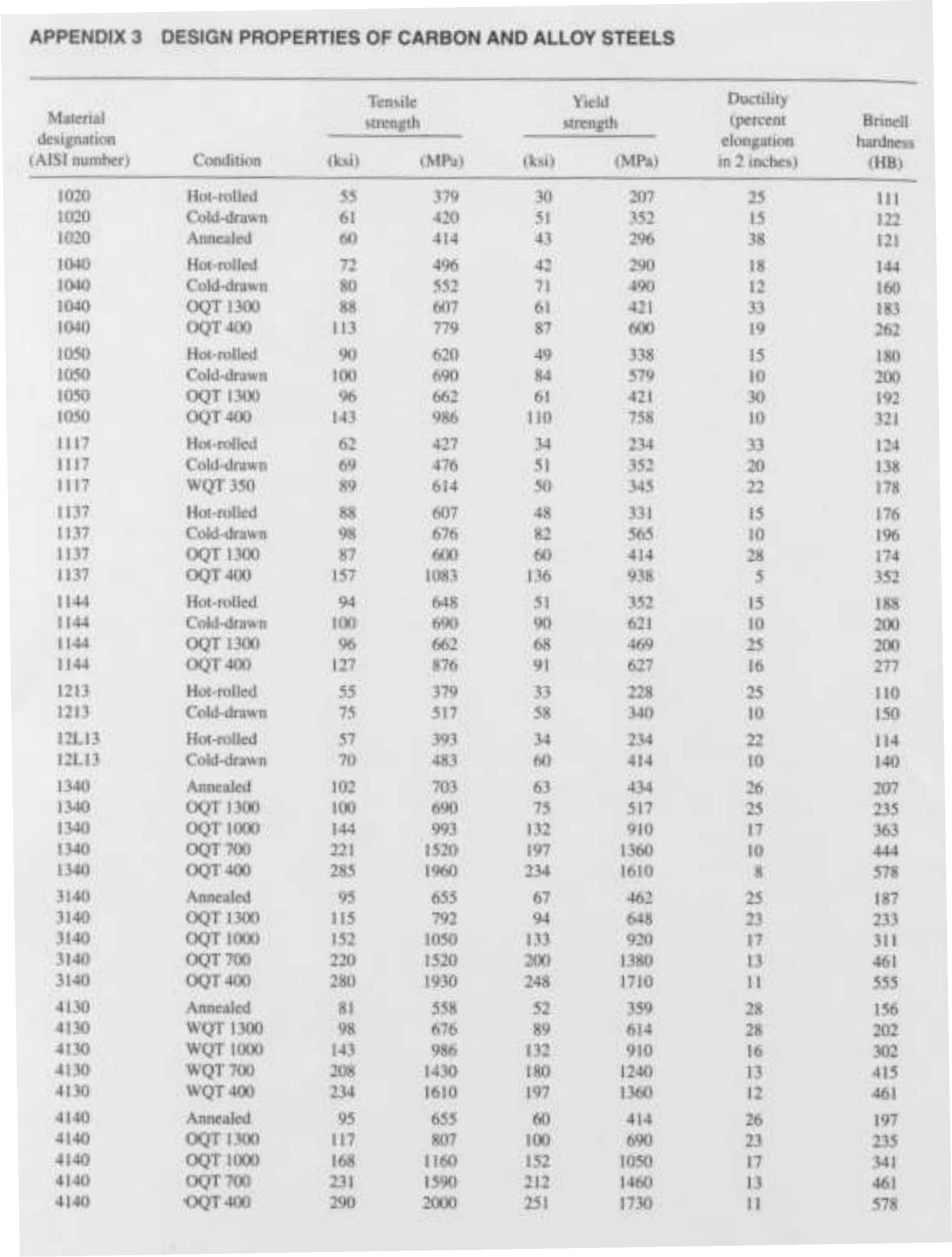
Treatment: Normalized at 1600 F; reheated to 1475 F; quenched in agitated oil. .530-in. Round Treated; .505-in. Round Tested. As-quenched HB 601.

FIGURE A4–6
Properties of heat-treated AISI 6150, oil-quenched and tempered (*Modern Steels and Their Properties*, Bethlehem Steel Co., Bethlehem, PA)

Treatment: Normalized at 1600 F; reheated to 1550 F; quenched in agitated oil. .565-in. Round Treated; .505-in. Round Tested. As-quenched HB 627.

Know These Basic HT Processes:

Spheroidizing: (must have carbon content of 0.6% or higher) Spheroidite forms when carbon steel is heated to approximately 700 °C for over 30 hours. Spheroidite can form at lower temperatures but the time needed drastically increases, as this is a diffusion-controlled process. The result is a structure of rods or spheres of cementite within primary structure (ferrite or pearlite, depending on which side of the eutectoid you are on). The purpose is to soften higher carbon steels and allow more formability. This is the softest and most ductile form of steel. The image to the right shows where spheroidizing usually occurs.



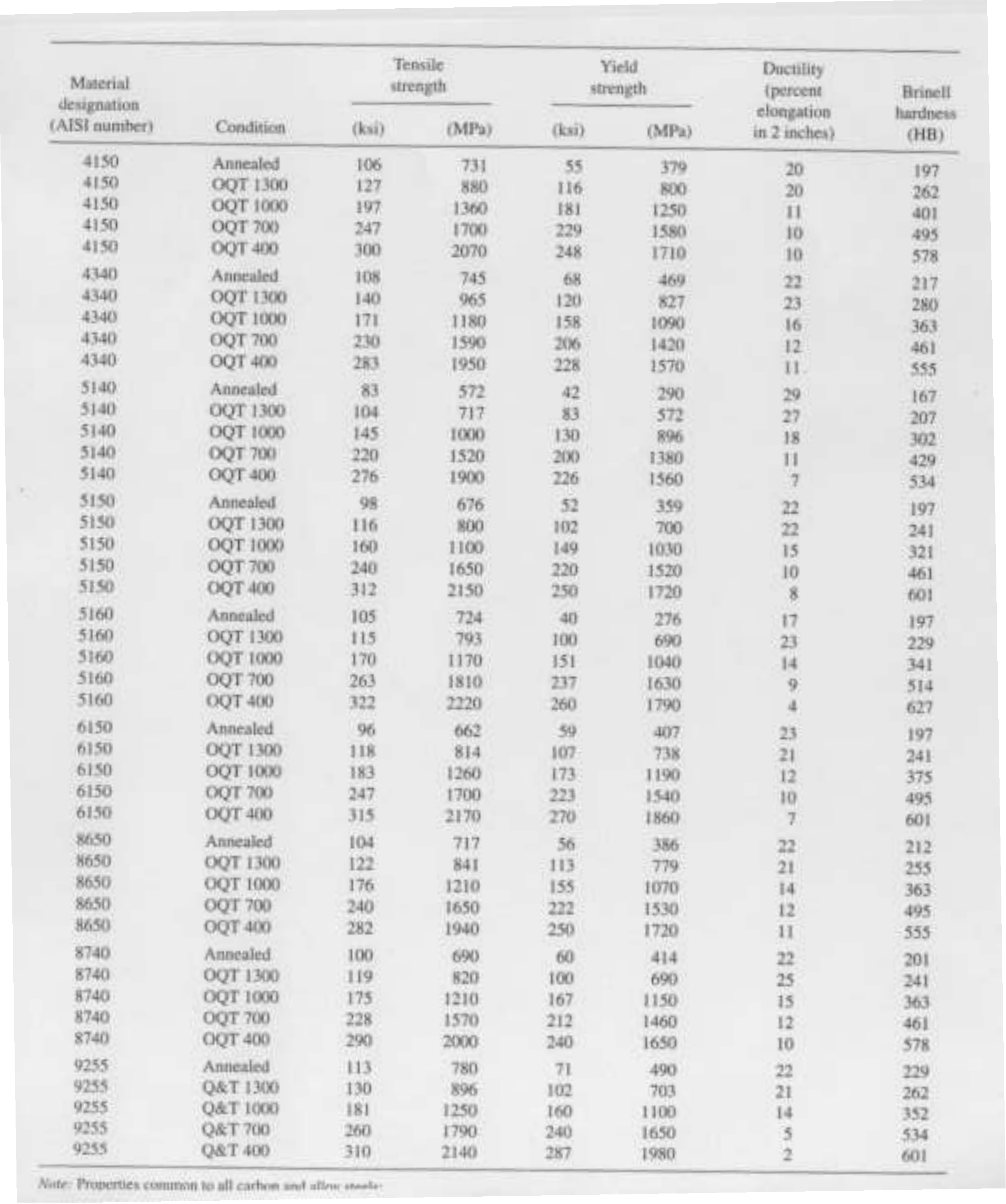
APPENDIX 3 DESIGN PROPERTIES OF CARBON AND ALLOY STEELS

Material designation (AISI number)	Condition	Tensile strength (ksi)	Tensile strength (MPa)	Yield strength (ksi)	Yield strength (MPa)	Ductility (percent elongation in 2 inches)	Brinell hardness (HB)
1020	Hot-rolled	55	379	30	207	25	111
1020	Cold-drawn	61	420	51	352	15	122
1020	Annealed	60	414	43	296	38	121
1040	Hot-rolled	72	496	42	290	18	144
1040	Cold-drawn	80	552	71	490	12	160
1040	OQT 1300	88	607	61	421	33	183
1040	OQT 400	113	779	87	600	19	262
1050	Hot-rolled	90	620	49	338	15	180
1050	Cold-drawn	100	690	84	579	10	200
1050	OQT 1300	96	662	61	421	30	192
1050	OQT 400	143	986	110	758	10	321
1117	Hot-rolled	62	427	34	234	33	124
1117	Cold-drawn	69	476	51	352	20	138
1117	WQT 350	89	614	50	345	22	178
1137	Hot-rolled	88	607	48	331	15	176
1137	Cold-drawn	98	676	82	565	10	196
1137	OQT 1300	87	600	60	414	28	174
1137	OQT 400	157	1083	136	938	5	352
1144	Hot-rolled	94	648	51	352	15	188
1144	Cold-drawn	100	690	90	621	10	200
1144	OQT 1300	96	662	68	469	25	200
1144	OQT 400	127	876	91	627	16	277
1213	Hot-rolled	55	379	33	228	25	110
1213	Cold-drawn	75	517	58	340	10	150
12L13	Hot-rolled	57	393	34	234	22	114
12L13	Cold-drawn	70	483	60	414	10	140
1340	Annealed	102	703	63	434	26	207
1340	OQT 1300	100	690	75	517	25	235
1340	OQT 1000	144	993	132	910	17	363
1340	OQT 700	221	1520	197	1360	10	444
1340	OQT 400	285	1960	234	1610	8	578
3140	Annealed	95	655	67	462	25	187
3140	OQT 1300	115	792	94	648	23	233
3140	OQT 1000	152	1050	133	920	17	311
3140	OQT 700	220	1520	200	1380	13	461
3140	OQT 400	280	1930	248	1710	11	555
4130	Annealed	81	558	52	359	28	156
4130	WQT 1300	98	676	89	614	28	202
4130	WQT 1000	143	986	132	910	16	302
4130	WQT 700	208	1430	180	1240	13	415
4130	WQT 400	234	1610	197	1360	12	461
4140	Annealed	95	655	60	414	26	197
4140	OQT 1300	117	807	100	690	23	235
4140	OQT 1000	168	1160	152	1050	17	341
4140	OQT 700	231	1590	212	1460	13	461
4140	OQT 400	290	2000	251	1730	11	578

HRS vs CRS
vs
Annealed?

HT?

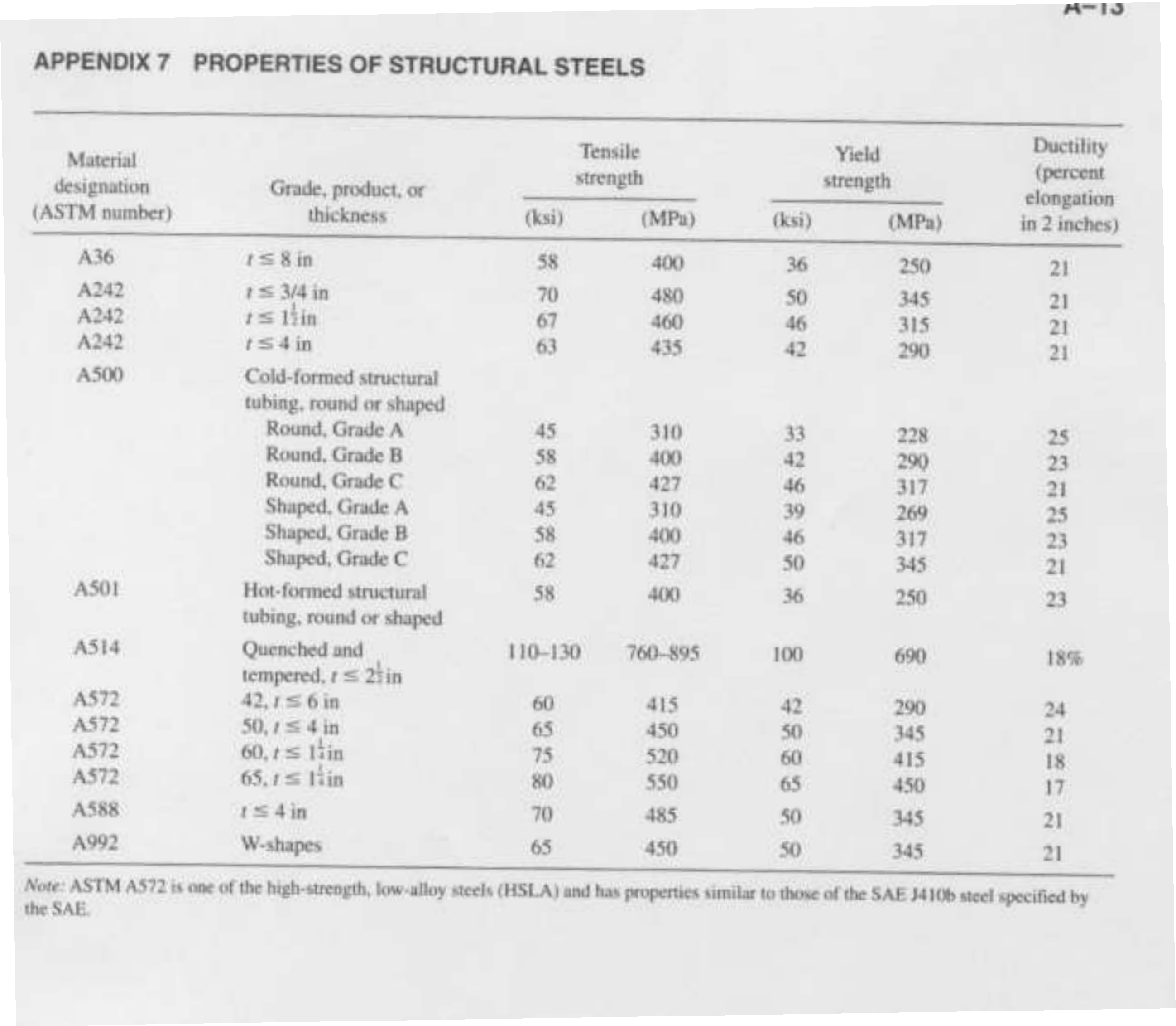
Tensile Strength and Elongation for Various Alloy Steels



Material designation (AISI number)	Condition	Tensile strength (ksi)	Tensile strength (MPa)	Yield strength (ksi)	Yield strength (MPa)	Ductility (percent elongation in 2 inches)	Brinell hardness (HB)
4150	Annealed	106	731	55	379	20	197
4150	OQT 1300	127	880	116	800	20	262
4150	OQT 1000	197	1360	181	1250	11	401
4150	OQT 700	247	1700	229	1580	10	495
4150	OQT 400	300	2070	248	1710	10	578
4340	Annealed	108	745	68	469	22	217
4340	OQT 1300	140	965	120	827	23	280
4340	OQT 1000	171	1180	158	1090	16	363
4340	OQT 700	230	1590	206	1420	12	461
4340	OQT 400	283	1950	228	1570	11	555
5140	Annealed	83	572	42	290	29	167
5140	OQT 1300	104	717	83	572	27	207
5140	OQT 1000	145	1000	130	896	18	302
5140	OQT 700	220	1520	200	1380	11	429
5140	OQT 400	276	1900	226	1560	7	534
5150	Annealed	98	676	52	359	22	197
5150	OQT 1300	116	800	102	700	22	241
5150	OQT 1000	160	1100	149	1030	15	321
5150	OQT 700	240	1650	220	1520	10	461
5150	OQT 400	312	2150	250	1720	8	601
5160	Annealed	105	724	40	276	17	197
5160	OQT 1300	115	793	100	690	23	229
5160	OQT 1000	170	1170	151	1040	14	341
5160	OQT 700	263	1810	237	1630	9	514
5160	OQT 400	322	2220	260	1790	4	627
6150	Annealed	96	662	59	407	23	197
6150	OQT 1300	118	814	107	738	21	241
6150	OQT 1000	183	1260	173	1190	12	375
6150	OQT 700	247	1700	223	1540	10	495
6150	OQT 400	315	2170	270	1860	7	601
8650	Annealed	104	717	56	386	22	212
8650	OQT 1300	122	841	113	779	21	255
8650	OQT 1000	176	1210	155	1070	14	363
8650	OQT 700	240	1650	222	1530	12	495
8650	OQT 400	282	1940	250	1720	11	555
8740	Annealed	100	690	60	414	22	201
8740	OQT 1300	119	820	100	690	25	241
8740	OQT 1000	175	1210	167	1150	15	363
8740	OQT 700	228	1570	212	1460	12	461
8740	OQT 400	290	2000	240	1650	10	578
9255	Annealed	113	780	71	490	22	229
9255	Q&T 1300	130	896	102	703	21	262
9255	Q&T 1000	181	1250	160	1100	14	352
9255	Q&T 700	260	1790	240	1650	5	534
9255	Q&T 400	310	2140	287	1980	2	601

Note: Properties common to all carbon and alloy steels:

Properties of Some Structural Steels – All use ASTM call-outs

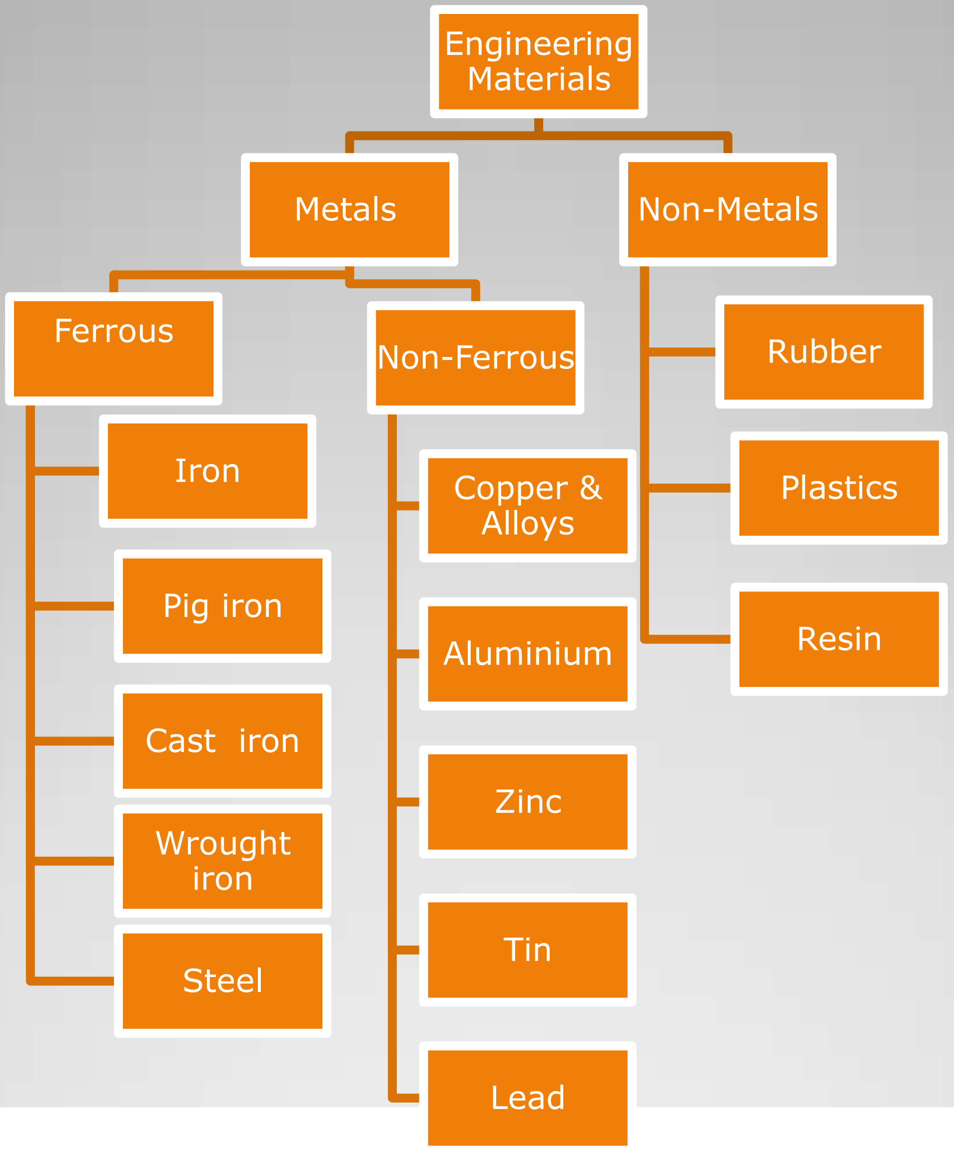


APPENDIX 7 PROPERTIES OF STRUCTURAL STEELS

Material designation (ASTM number)	Grade, product, or thickness	Tensile strength (ksi)	Tensile strength (MPa)	Yield strength (ksi)	Yield strength (MPa)	Ductility (percent elongation in 2 inches)
A36	$t \le 8$ in	58	400	36	250	21
A242	$t \le 3/4$ in	70	480	50	345	21
A242	$t \le 1\frac{1}{2}$ in	67	460	46	315	21
A242	$t \le 4$ in	63	435	42	290	21
A500	Cold-formed structural tubing, round or shaped					
	Round, Grade A	45	310	33	228	25
	Round, Grade B	58	400	42	290	23
	Round, Grade C	62	427	46	317	21
	Shaped, Grade A	45	310	39	269	25
	Shaped, Grade B	58	400	46	317	23
	Shaped, Grade C	62	427	50	345	21
A501	Hot-formed structural tubing, round or shaped	58	400	36	250	23
A514	Quenched and tempered, $t \le 2\frac{1}{2}$ in	110–130	760–895	100	690	18%
A572	42, $t \le 6$ in	60	415	42	290	24
A572	50, $t \le 4$ in	65	450	50	345	21
A572	60, $t \le 1\frac{1}{4}$ in	75	520	60	415	18
A572	65, $t \le 1\frac{1}{4}$ in	80	550	65	450	17
A588	$t \le 4$ in	70	485	50	345	21
A992	W-shapes	65	450	50	345	21

Note: ASTM A572 is one of the high-strength, low-alloy steels (HSLA) and has properties similar to those of the SAE J410b steel specified by the SAE.

Ferrous and Non-Ferrous Metals



- Engineering Materials
  - Metals
    - Ferrous
      - Iron
      - Pig iron
      - Cast iron
      - Wrought iron
      - Steel
    - Non-Ferrous
      - Copper & Alloys
      - Aluminium
      - Zinc
      - Tin
      - Lead
  - Non-Metals
    - Rubber
    - Plastics
    - Resin

- **Metal** is an element, compound or alloy that is a good conductor of both electricity and heat

- **Metal crystal structure** and specific metal properties are determined by **metallic bonding** – force, holding together the atoms of a metal

Metals

Ability of the valence free electrons to travel throughout the solid explains both the high electrical conductivity and thermal conductivity of metals.

Metals

Other specific metal features are: **luster** or shine of their surface (when polished), their **malleability** (ability to be hammered) and **ductility** (ability to be drawn).

These properties are also associated with the metallic bonding and presence of free electrons in the crystal lattice.

Metals

- Iron
  - Pig iron
  - Cast iron
    - white cast iron
    - grey cast iron
  - Wrought iron

Ferrous metals

- **Iron** (Fe) – atomic number 26

- most widely used of all metals as base metal in steel and cast iron

- **Pig iron** - the intermediate product of smelting iron ore with a high-carbon fuel such as coke, usually with limestone as a flux

Iron

- **Cast iron** – is derived from pig iron
  - **White cast iron** is named after its white surface when fractured, due to its carbide impurities which allow cracks to pass straight through.
  - **Grey cast iron** is named after its grey fractured surface, which occurs because the graphitic flakes deflect a passing crack and initiate countless new cracks as the material breaks.

Cast iron

Wrought iron

- **Wrought iron** - iron alloy with a very low carbon content, in comparison to steel, and has fibrous inclusions (slag)
- tough, malleable, ductile and easily welded

- **Steel**
  - **Cast steel**
  - **Stainless steel**
  - **High-speed steel**

Steel

- **Steel** is an alloy that consists mostly of iron and has a carbon content between 0.2% and 2.1% by mass

- Carbon is the most common alloying material for iron, but various other alloying elements are used, such as **manganese, chromium, vanadium, molybdenum, tungsten, etc.**

Steel

- **Stainless steel** (**inox steel**) is a steel alloy with a minimum of 10.5 or 11% chromium content by mass.
- It does not corrode, rust, or stain with water as ordinary steel does.

Stainless steel

- **High speed steel** is commonly used in tool bits and cutting tools.

- It can withstand higher temperatures without losing its hardness. This property allows HSS to cut faster than high carbon steel, hence the name *high speed steel*.

High-speed steel

1. Preparation of iron ore
    - Crushing
    - Screening
    - Roasting with limestone and coke in blast furnace

2. Pig iron = crude iron

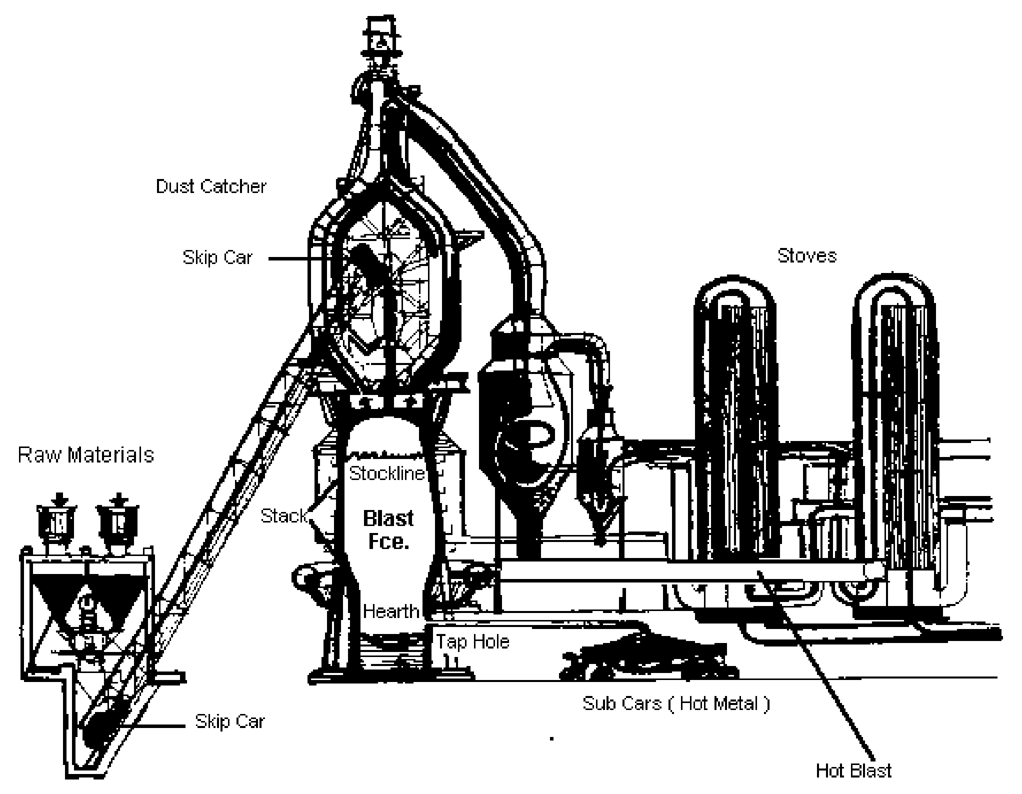
   Main impurities: - carbon, silicon, manganese, sulphur, phosphorus

The production of steel

4. Cast iron – obtained by remelting pig

5. Steel alloys - to reach higher tensile strength, yield point, endurance limit, impact strength

The production of steel



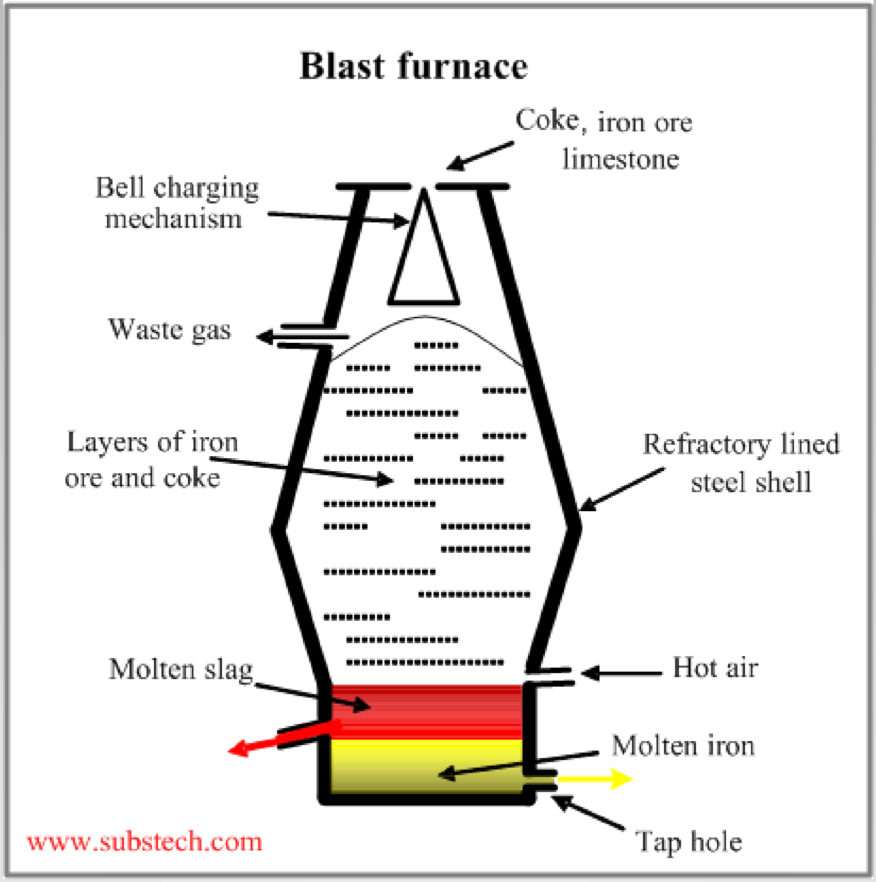
Blast furnace

- A **blast furnace** is a type of metallurgical furnace used for smelting industrial metals, generally iron.
- In a blast furnace, fuel, ore and limestone as flux are continuously supplied through the top of the furnace, while air (sometimes with oxygen enrichment) is blown into the bottom of the chamber, so that chemical reactions take place throughout the furnace as the material moves downward.

Blast furnace

- The end products are usually molten metal and slag phases tapped from the bottom, and flue gases exiting from the top of the furnace.

Blast furnace



Blast furnace

- Copper
- Aluminium
- Zinc
- Tin
- Lead

Non-ferrous metals

- **Copper –** Latin *cuprum* **(Cu)** – ranks next to iron in importance and wide range of application

- good heat and electrical conductivity

- resistance to corrosion

- **Alloys**: brass, bronze, cupro- nickel (copper nickel) alloys

Copper & Alloys

- **Aluminium (BrE)** or **aluminum** (**AmE**) – Al, atomic number 13
- whitish with bluish cast
- the third most abundant element (after oxygen and silicon), and the most abundant metal in the Earth’s crust

Aluminium

- low density and ability to resist corrosion; good conductivity

- structural components made from aluminium and its alloys are vital to the aerospace industry and are important in other areas of transportation and structural materials

Aluminium

Zinc

- **Zinc (Zn)**, atomic number 30
- bluish white
- corrosion resistant in air due to a thin oxide film forming on its surface
- used as a coating for protecting steel - **galvanisation** (or **galvanisation**) is the process of applying a protective zinc coating to steel or iron, in order to prevent rusting

Tin

- **Tin** – Latin *stannum* **(Sn)**, atomic number 50
- white, lustrous, soft, malleable, ductile, resistant to corrosion
- used as coating for steel and sheet iron
- **white metal** – tin based alloy with amounts of lead, copper and antimony – lining material

Lead

- **Lead** – Latin *plumbum* **(Pb)**, atomic number 82
- metallic lead has a bluish-white colour after being freshly cut, but it soon tarnishes to a dull grayish color when exposed to air
- has a shiny chrome-silver luster when it is melted into a liquid

Lead

- soft, malleable, has little ductility
- **usage**: plates for storage batteries, covering for electrical cables

- **Non-Metals** are poor conductors of heat and electricity when compared to metals as they gain or share valence electrons easily (as opposed to metals which lose their valence electrons easily)

- usually have lower densities than metals;
  they have significantly lower melting points and boiling points than metals

- brittle, non-ductile, dull (do not posses metallic luster)

Non-Metals

- **Plastics**
- **Thermosetting polymer**
  - **Epoxy resin**
- **Thermoplastic**
- **Rubber**

Non-Metals

- **Plastics:**
- immune to corrosion
- insulator
- unsuitable for higher temperatures
- to improve their properties additives are given

Plastics

- A **thermosetting plastic**, also known as a **thermoset**, is polymer material that irreversibly cures. The cure may be done through heat (generally above 200 °C), through a chemical reaction (two-part epoxy, for example).

Thermosetting plastic

- **Thermoset materials** are usually liquid or malleable prior to curing and designed to be molded into their final form, or used as adhesives. Others are solids like that of the molding compound used in semiconductors and integrated circuits (IC).
- Once hardened, a thermoset resin cannot be reheated and melted back to a liquid form.

Thermosetting plastic

Epoxy resin – thermosetting plastic

- **usage**: chocking materials

Epoxy resins

- **Thermoplastic**, also known as a **thermosoftening plastic** is a polymer that turns to a liquid when heated and freezes to a very glassy state when cooled sufficiently.
- Thermoplastic polymers differ from thermosetting polymers in that they can be remelted and remoulded.

Thermoplastic

- **Rubber**
- rough, elastic material
- unaffected by water
- attacked by oil and steam
- **usage**: gaskets, flexible couplings, vibration mount

Rubber

Introduction to Materials & Testing

Types of Testing

- Destructive testing is changes the dimensions or physical and structural integrity of the specimen. (It is essentially destroyed during the test)

  e.g., Tensile, Compression, Shear and Rockwell Hardness

- Non-Destructive testing does not affect the structural integrity of the sample.

(A measurement that does not effect the specimen in any way) e.g., weighing, measurements etc.

Mechanical Testing

UltimateTensile Strength - The maximum tensile stress that a material is capable of developing during a test.

Load- Applied force either pounds or newtons

Stress - The intensity of the internally-distributed forces or components of forces that resist a change in the form of a body. Commonly measured in units dealing with force per unit area, such as pounds per square inch (PSI or lb/in^2) or Megapascals (Mpa). The three basic types of stress are tension, compression, and shear. The first two, tension and compression, are called direct stresses.

Elastic Limit - The greatest amount of stress a material can develop without taking a permanent set.

Percent Elongation - The total percent strain that a specimen develops during testing.

Principal properties determined through tensile testing include yield strength, tensile strength, ductility (based on the percent elongation and percent reduction in area), modulus of elasticity, and visual characteristics of the fracture. For brittle materials, which do not show a marked yield or ductility, data is collected for tensile strength and type and condition of fracture.

Expected Results

The results of tensile testing can be used to plot a stress-strain curve which illustrates the tensile properties of the material. Stress (in pounds per square inch or Pascal's) is plotted on the vertical axis while strain (inches per inch, millimeters per millimeter, or unit less) is plotted along the horizontal.

As the load is applied, the curve is proportional and this period of linearity is termed the elastic region. Once the curve deviates from a straight line and begins to yield, the material has reached the proportional limit. Once the material has yielded, it exhibits plastic behavior or plasticity. Brittle materials do not exhibit much yield and are, therefore, less curved than ductile materials.

Modulus of Elasticity - Also known as Young’s modulus; calculated by finding the slope of the stress-strain curve for a given material within the range of its linear proportionality between stress and strain.

Proportional Limit - The greatest stress a material can develop without deviating from linearity between stress and strain. Otherwise stated, the greatest stress developed in a material within its elastic range.

Percent Reduction in Area - The difference between the original and final cross-sectional areas of a test piece, expressed as a percentage.

Yield Point – Also referred to as ***Elastic Limit***, is the point at which any additional stress will result in permanent deformation.

Yield Strength - The stress at which a material exhibits a specified limiting permanent set.

Tensile Test - Introduction

- The tensile test is a common test performed on metals, wood, plastics, and most other materials.

- Tensile loads are those that tend to pull the specimen apart, putting the specimen in tension. They can be performed on any specimen of known cross-sectional area and gage length to which a uniform tensile load can be applied.

- Tensile tests are used to determine the mechanical behavior of materials under static, axial tensile, or stretch loading.

- ASTM standards for common tensile tests may be found in sections E8 (metals), D638 (plastics), D2343 (fibers), D897 (adhesives), D987 (paper), and D412 (rubber).

The engineering stress is:

$$\sigma = \frac{P}{A_0}$$

P is the load in lbs. on the specimen and A_0 is the original cross-sectional area near the center of the specimen.

On the other hand, the true stress is the load divided by the true area, which continues to be smaller by the tensile load.

The true stress continues to increase to the point of fracture, while the engineering stress decreases to the point of fracture due to the increasing load and the constant cross-sectional area.

The engineering strain is:

$$\varepsilon = \frac{l - l_0}{l_0}$$

l is the gage length at a given load and l_0 is the original gage length with zero load

Modulus of Elasticity

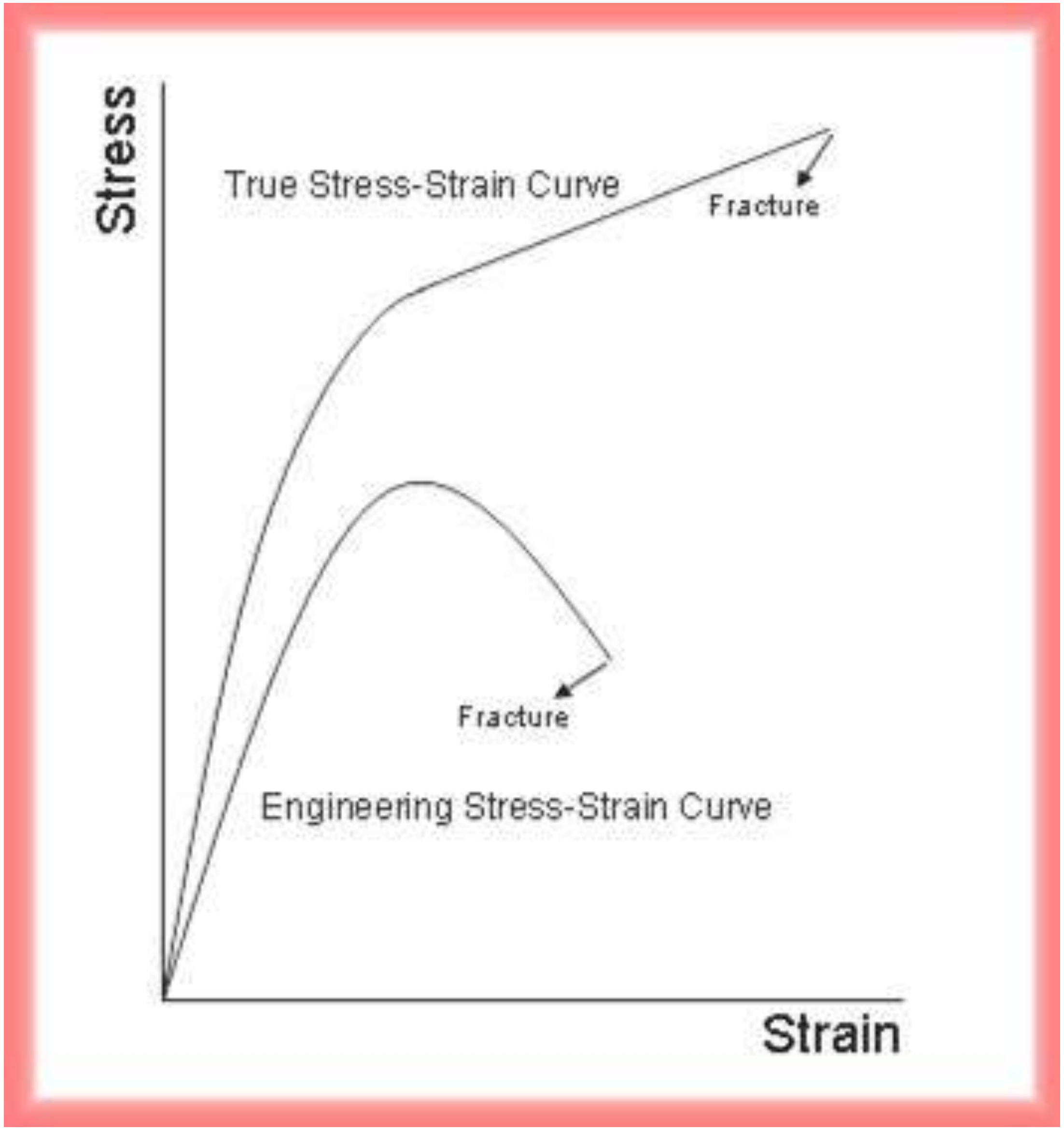
- The slope of the stress-strain curve in the elastic deformation region is the modulus of elasticity, which is known as Young's modulus

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

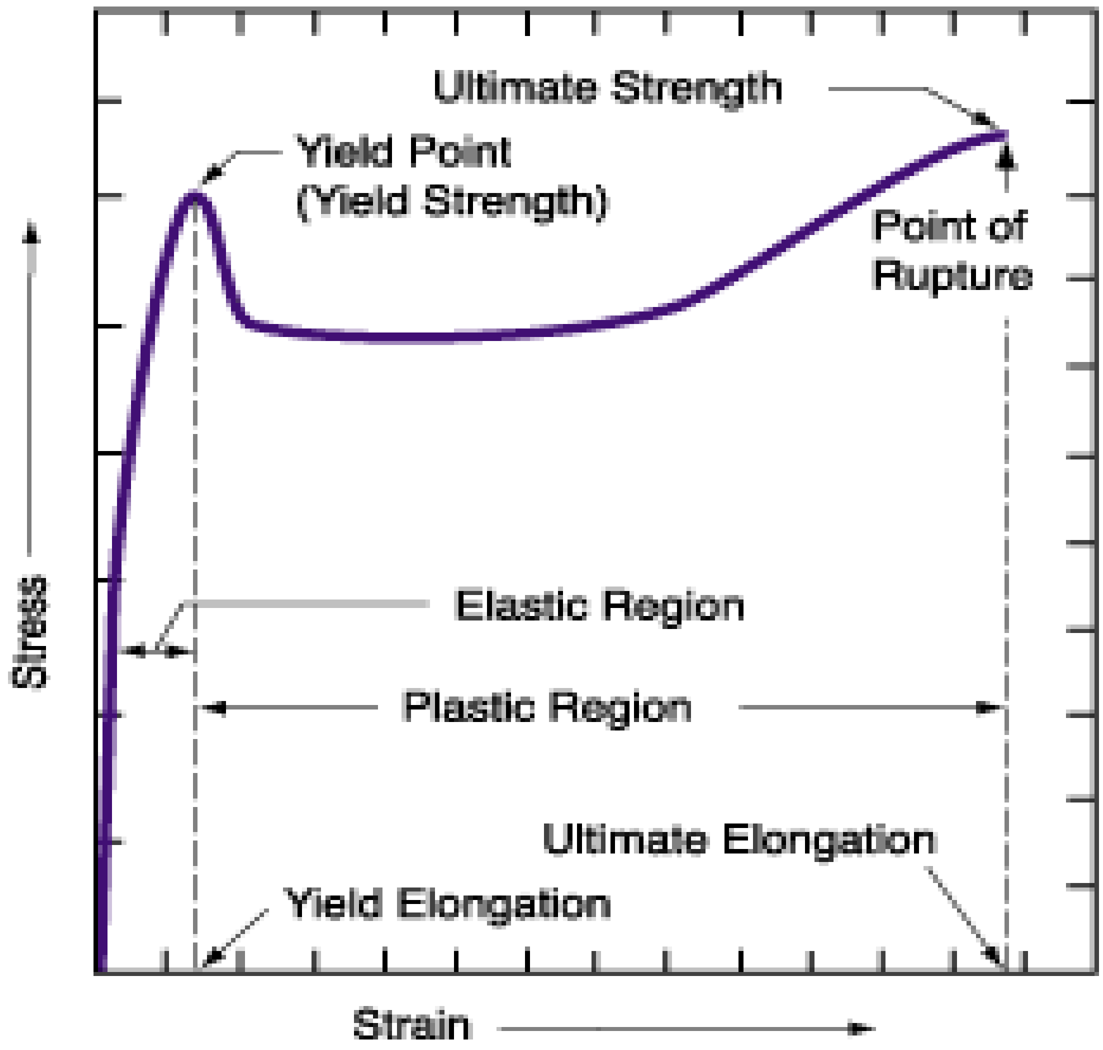
Material Fracture: Background

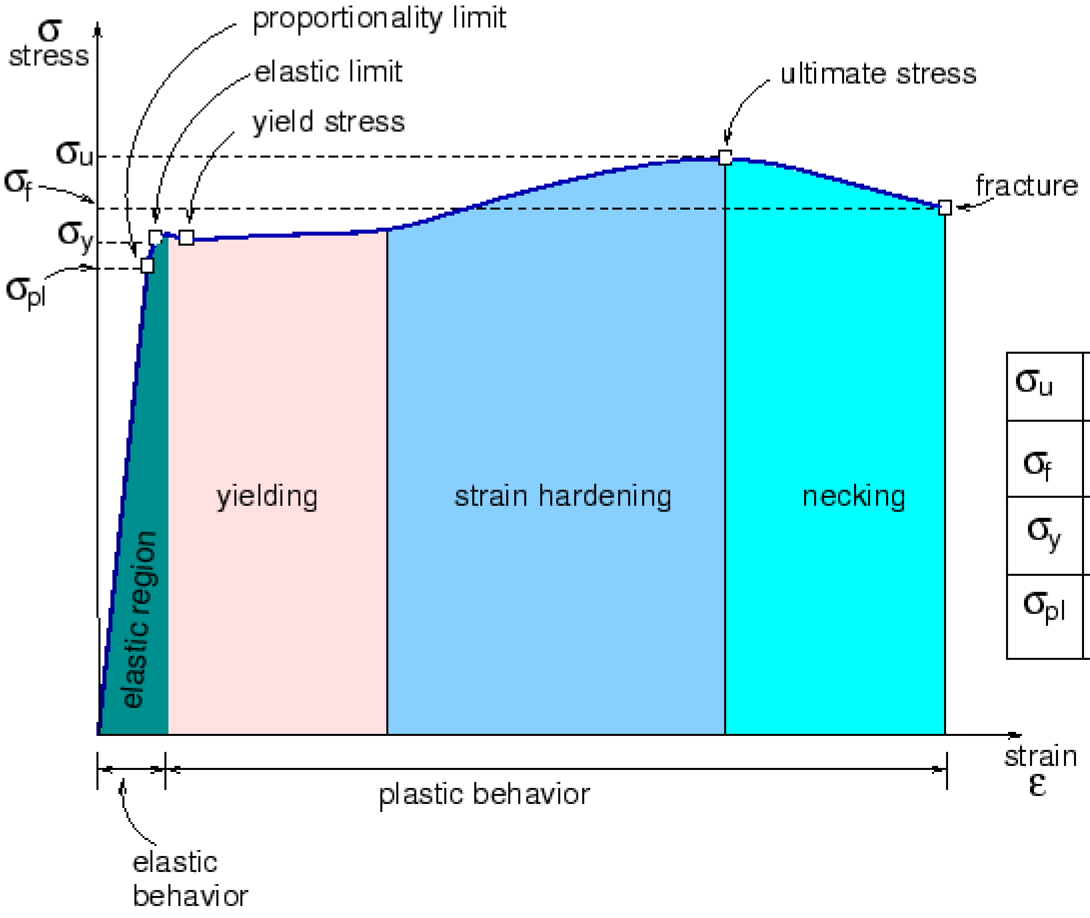
Stress-Strain Curve

This stress-strain curve is produced from the tensile test.



Typical Stress-Strain Curve

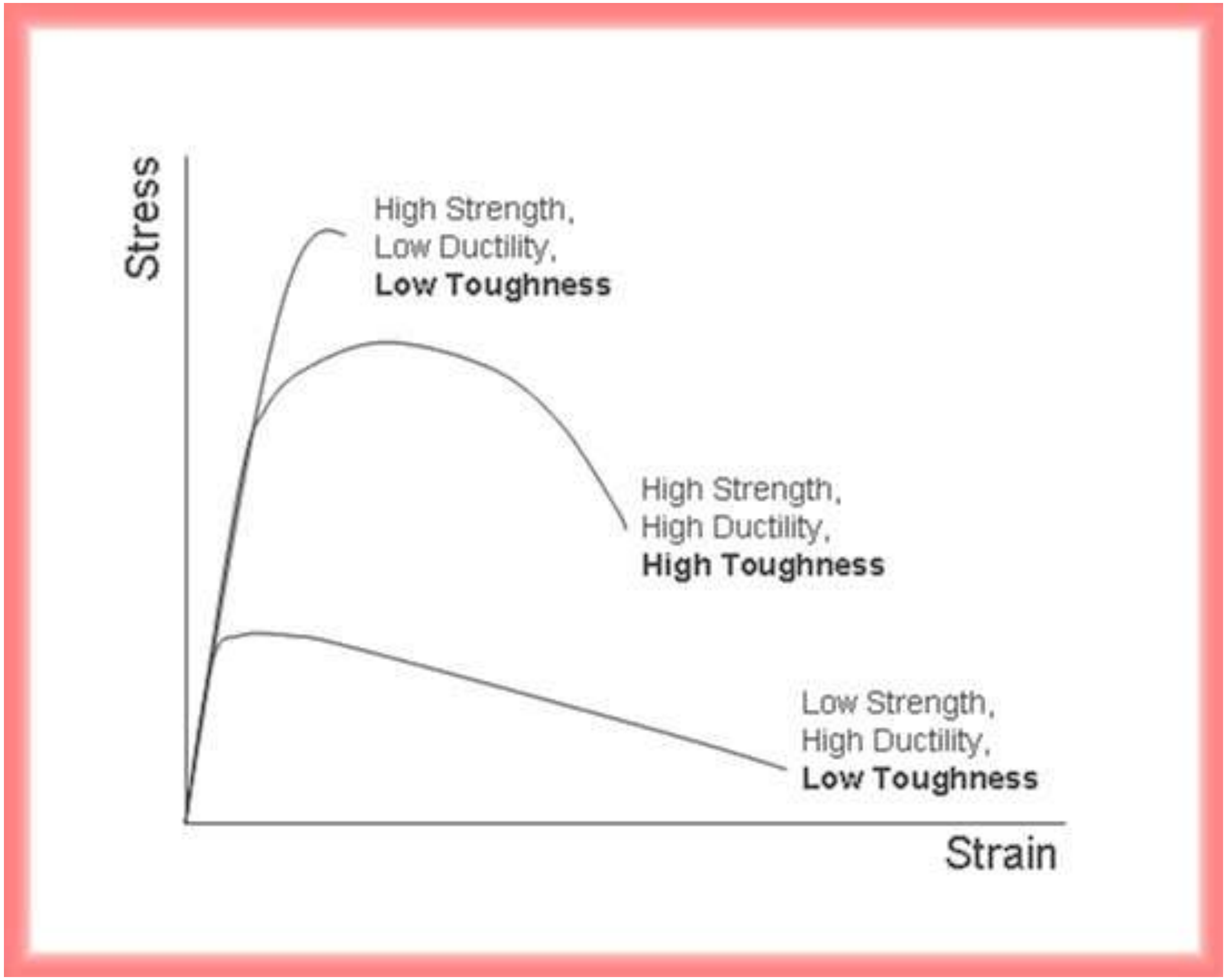




σ_u	Ultimate stress
σ_f	Fracture stress
σ_y	Yield stress
σ_{pl}	Proportionality limit

Figure 4: Necking in a tensile specimen.

Stress Strain for Different Materials



Tensile Testing - Procedure

- Tensile tests are used to determine the tensile properties of a material, including the tensile strength. The tensile strength of a material is the maximum tensile stress that can be developed in the material.

- In order to conduct a tensile test, the proper specimen must be obtained. This specimen should conform to ASTM standards for size and features. Prior to the test, the cross-sectional area may be calculated and a pre-determined gage length marked.

- The specimen is then loaded into a machine set up for tensile loads and placed in the proper grippers. Once loaded, the machine can then be used to apply a steady, continuous tensile load.

- Data is collected at pre-determined points or increments during the test. Depending on the material and specimen being tested, data points may be more or less frequent. Data include the applied load and change in gage length. The load is generally read from the machine panel in pounds or kilograms.

•The change in gage length is determined using an extensometer. An extensometer is firmly fixed to the machine or specimen and relates the amount of deformation or deflection over the gage length during a test.

•While paying close attention to the readings, data points are collected until the material starts to yield significantly. This can be seen when deformation continues without having to increase the applied load. Once this begins, the extensometer is removed and loading continued until failure. Ultimate tensile strength and rupture strength can be calculated from this latter loading.

•Once data have been collected, the tensile stress developed and the resultant strain can be calculated. Stress is calculated based on the applied load and cross-sectional area. Strain is the change in length divided by the original length.

Compression Testing - Introduction

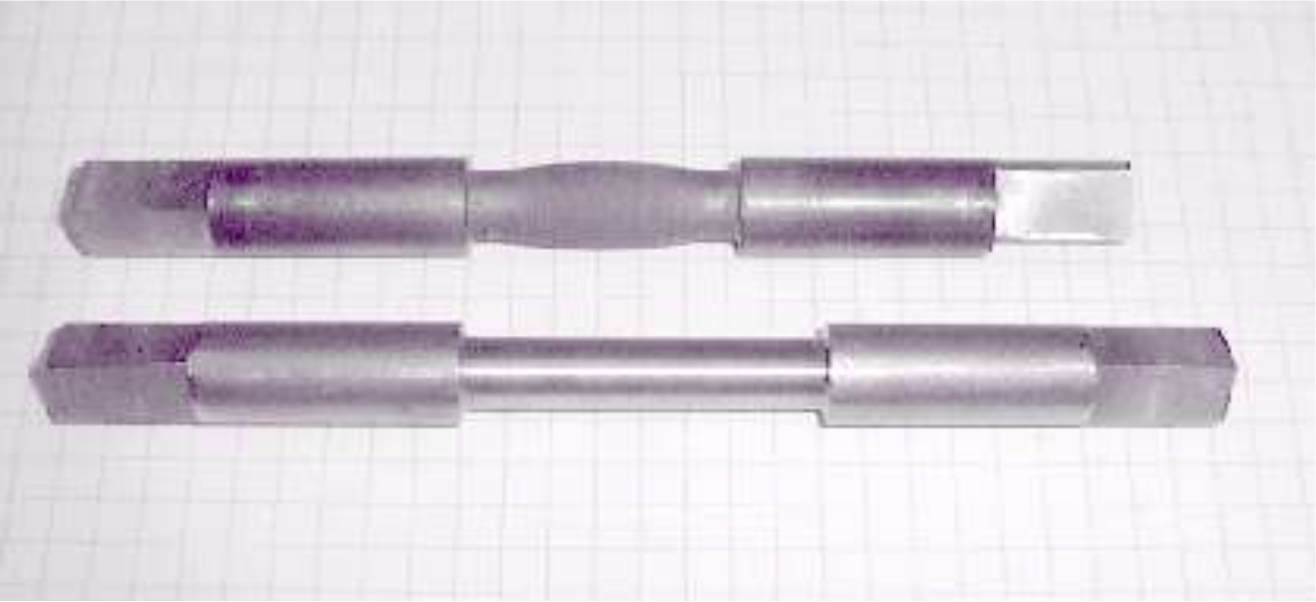
- Simplistically, compression testing is the opposite of tensile testing. A compressive load tends to squeeze or compact the specimen. The choice of a compression test over other types of testing largely depends on the type of loading the material will see during application or service.

- Metals and many plastics, for example, are more efficient at resisting tensile loads. Therefore, they are more commonly tested using tensile loading, depending on the application, of course. Materials, such as concrete, brick, and some ceramic products, are more often used in applications for their compressive loading properties and are, therefore, tested in compression. Again, it is important to choose the test that best reflects the loads and conditions the material will be subjected to in application or service.

Compression Testing – Procedure

During a typical compression test, data are collected regarding the applied load, resultant deformation or deflection, and condition of the specimen. For brittle materials, the compressive strength is relatively easy to obtain, showing marked failure. However, for ductile materials, the compressive strength is generally based on an arbitrary deformation value. Ductile materials do not exhibit the sudden fractures that brittle materials present. They tend to buckle and "barrel out".

Barreling or Bulging of a Sample under Compressive Loads



- Prior to this and any test, the dimensions of the specimen should be measured with adequate precision using proper instruments. Once these measurements have been taken and recorded, the specimen should be loaded into the testing machine.

- In compression testing, and testing in general, care should be taken to insure that the axis of the specimen is centered and aligned with the axis of loading.

- Loading rates should be steady and continuous. Rates vary, but a general figure is 0.005 inches per minute strain rate. Loading rates typically range from 500-1000 lb/min.

- As in most tests of mechanical properties, the loading rate can adversely affect the results if you get carried away. Loading continues at this rate up to approximately one-half of the anticipated strength and, then, should be reduced to allow for more frequent data collection. In this way, subtle changes can be observed in the specimen's behavior.

- As in all of these tests, please observe proper safety procedures. Obtain and properly wear personal protective equipment. Some of these materials exhibit violent fractures with explosive results.

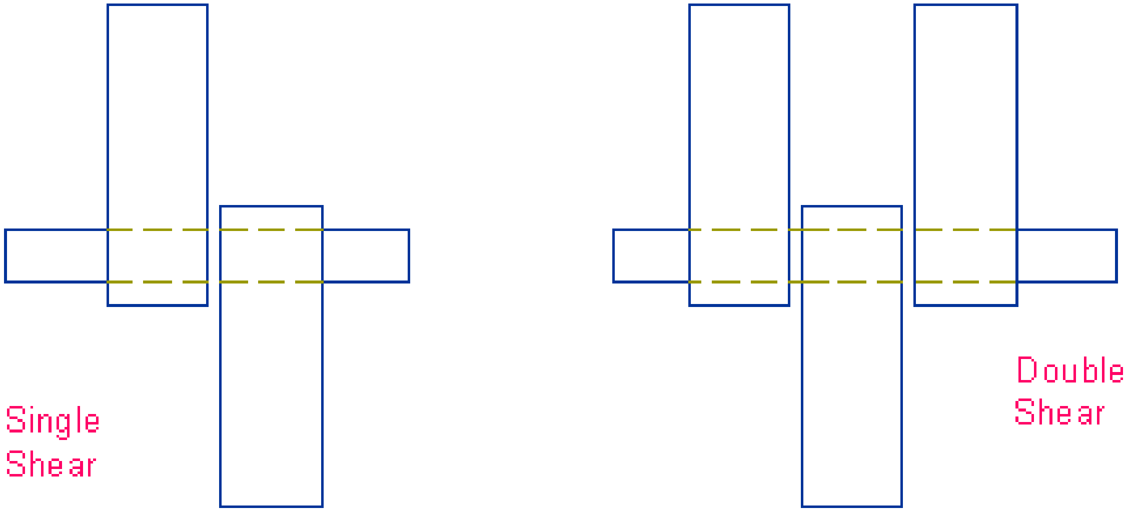
Shear Testing - Introduction

•Shear testing involves an applied force or load that acts in a direction parallel to the plane in which the load is applied. Shear loads act differently than, say, tensile or compressive loads that act normal or perpendicular to the axis of loading. Direct shear and torsional shear are important forces used to determine shear properties. Direct or torsional loading depends on the forces a material is expected to be subjected to during service.

Shear Testing - Procedure

•Before testing, the specimen is accurately measured using proper instruments and the gage length is marked. The troptometer or a suitable replacement is attached to the specimen and zeroed out. Proper precautions should be taken to center the specimen in the machine or fixture. The grippers are tightened to insure against slippage, yet not so tight as to cause deformations which would affect test results.

•In general, shear testing involves either direct or torsional loading. In direct shear tests, the specimen is placed in the shear test fixture and a load is applied. This can be seen in the figure below. For plate specimens, a punch and die combination may be used. Plastics, generally, are square specimens with holes in either end to facilitate gripping. The applied load and resultant deformation are recorded and a suitable graph can be plotted.



Transverse Shear Test Fixture

Impact Testing – Introduction

- A specimen under test will exhibit different properties, depending on the rate at which the load is applied. For example, most materials will exhibit greater strength is the load is applied in a slower, gentler manner (static loading) than suddenly (dynamic). Because properties are strain-rate dependent, tests have been standardized to determine the energy required to break materials used sudden blows. These are termed impact tests.

- Impact tests generally involve sudden shock loading that results in breakage of the specimen. The result is calculated based on the energy required to break the specimen and the resultant loss of momentum. This can be calculated if one knows the initial energy and final energy or the initial angle and final angle of the object used to break the specimen. The Izod and Charpy tests are commonly used to measure impact strength. They differ only slightly, the configuration and specifications of the test specimen.

Hardness Testing - Introduction

- Hardness, as a mechanical property, is the resistance of a material to surface penetration. Therefore, most hardness tests involve measuring the amount of force required to implant a specified indentation in the surface of a specimen OR the size of the indentation produced from applying a specified load. The indenter used varies with the test selected, but is generally hardened steel or diamond.

- Other types of hardness tests involve the rebound of a dynamic or impact load, such as the scleroscope. The amount of rebound that results is used as an indication of the surface hardness of the specimen.

- Common hardness tests include the Rockwell and Brinell. Other test procedures used include the scleroscope, surface abrasion testing, Vickers, and Tukon-Knoop.

Rockwell Hardness Test

- The Rockwell hardness test relies on a specified load and the size of the indentation or penetration made to determine the hardness value. Rockwell hardness tests involve selecting the magnitude of the load to apply based on the suspected hardness of the specimen. Rockwell tests, however, use a variety of indenters, depending on the material and suspected hardness.

- The Rockwell hardness test provides more direct results. A specially-designed testing machine is typically used and provides a dial reading for the Rockwell Hardness Number, so no special calculations or measurements are necessary.
  In the Rockwell hardness test, the specimen is loaded on a platen and raised with an elevating screw to contact the indenter, the indenter having been selected for the material and hardness being scrutinized and previously installed in the testing machine.

- The indenter may be a 1/16 inch hardened steel ball, a 1/8 inch hardened steel ball, or a 120° diamond cone ground to a point, called a brale. Once the specimen is loaded, the platen is raised to contact the indenter to a specified set point on the machine's readout. This point is used to indicate that the minor load has been applied. By raising the platen and specimen against the indenter, a small, minor load drove the indenter into the specimen to initially set the indenter into the specimen. The minor load is typically 10 kg.

- The major load may now be released to drive the indenter further into the specimen. Major loads typically range from 60-100 kg when the steel ball is used and 150 kg when the brale is used. Once the major load has been released, sufficient time is allowed for the dial to come to rest, generally between 30 and 60 seconds, depending on the material.

- The major load is then removed and the Rockwell Hardness Number read directly from the readout on the machine with the minor load remaining. This provides a value based on the distance the indenter was driven into the specimen by the major load. Once the reading is taken, the elevating screw is used to release the minor load and the specimen may be removed.

Rockwell Scales

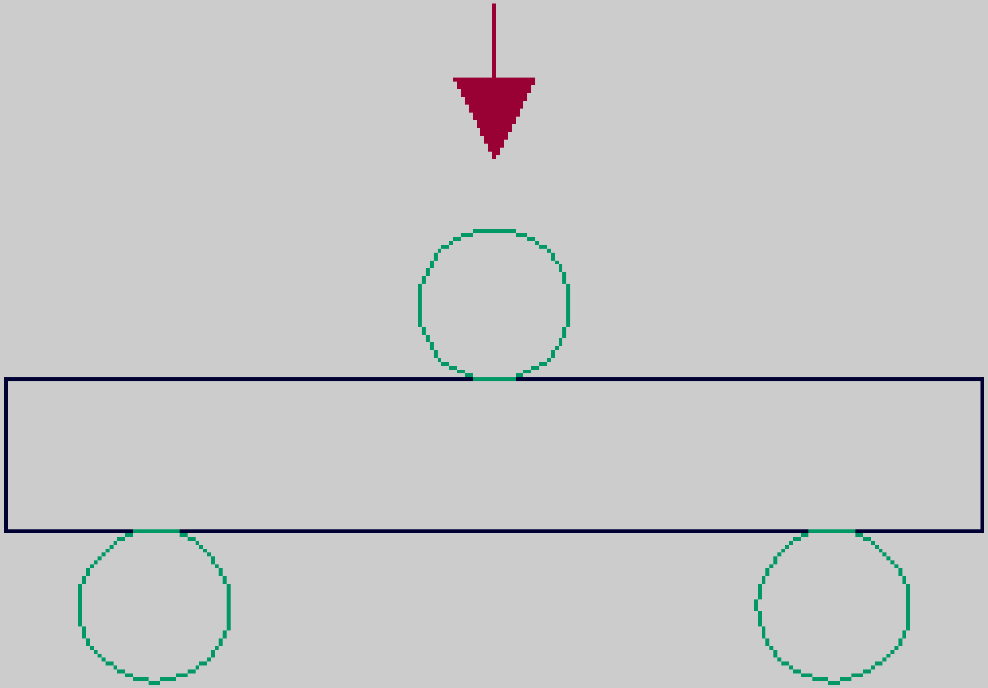
Scale	Indenter	Applied Load (kg)
A	Brale	60
B	1/16-inch ball	100
C	Brale	150
D	Brale	100
E	1/8-inch ball	100
F	1/16-inch ball	60
G	1/16-inch ball	150

Flexure Testing - Introduction

Forces that tend to induce compressive stresses over one part of a cross-section and tensile stresses over the remainder are described as bending or flexural forces. Bending can be accompanied by direct stresses, transverse shear, or torsional shear, depending on loading. Bending action in beams is often termed flexure, referring to transverse loading of the beam. The deflection of the specimen is the displacement of a point on the neutral axis of the beam from its original position under the action of the applied loads. The figure, the deflection, is an indication of the overall stiffness of the material.

Flexure or Bend Testing - Procedure

In flexure or bend testing, the specimen is typically loaded flat on two solid support rods. A third rod is used for loading. This setup helps insure three-point loading which allows the tensile forces to act from the center loading point outward toward the two support rods. Once the specimen has been accurately measured using proper instruments and the machine properly set up, loading continues in a slow, steady manner. The flexure strength and modulus of rupture may be calculated based on these data. A load-versus-deflection curve or stress-strain curve can be plotted based on the data.

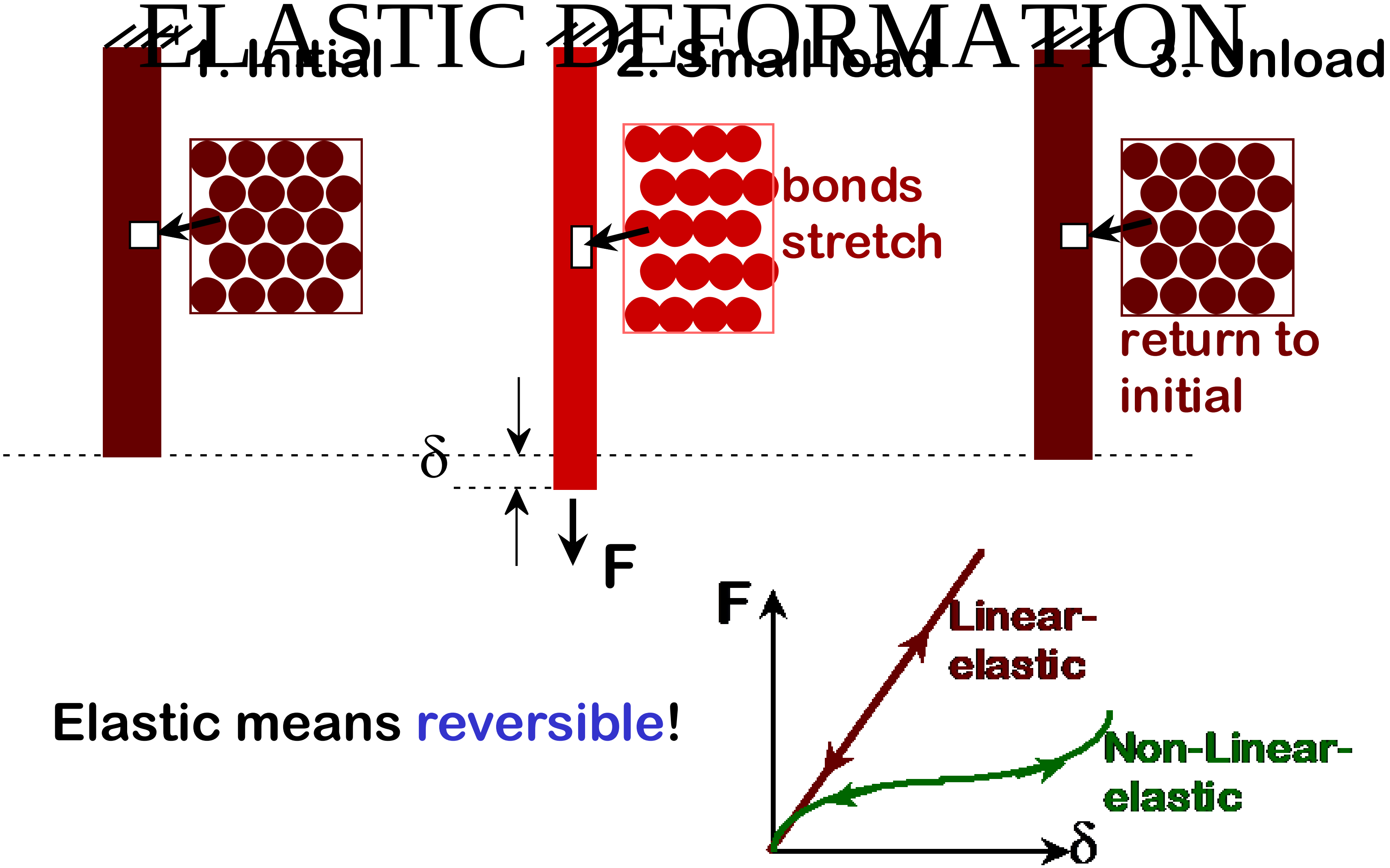


Typical Flexure Testing Setup

ISSUES TO ADDRESS...

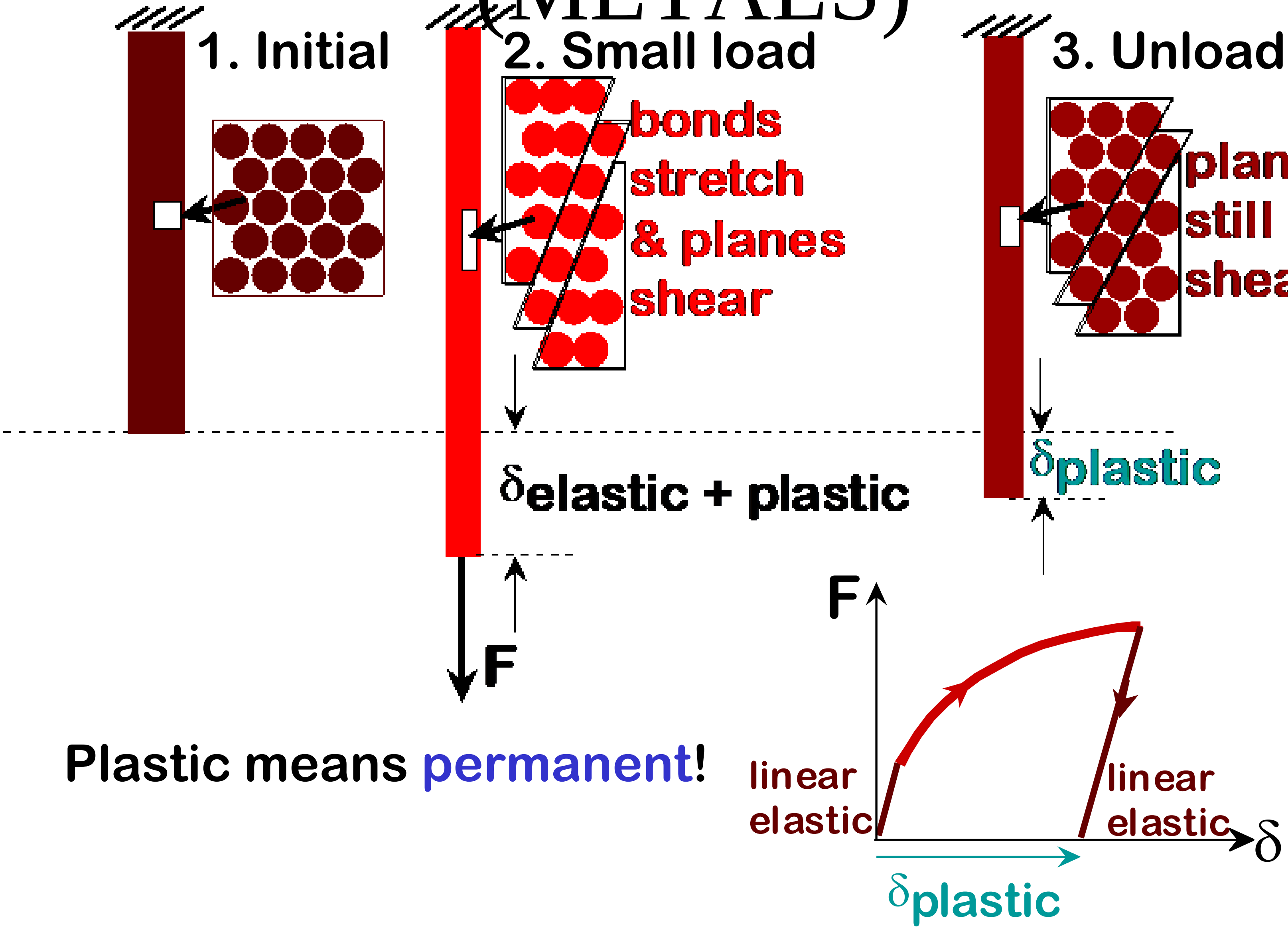
- Stress and strain: What are they and why are they used instead of load and deformation?
- Elastic behavior: When loads are small, how much deformation occurs? What materials deform least?
- Plastic behavior: At what point do dislocations cause permanent deformation? What materials are most resistant to permanent deformation?
- Toughness and ductility: What are they and how do we measure them?
- **Ceramic Materials:** What special provisions/tests are made for ceramic materials?

ELASTIC DEFORMATION



Elastic means **reversible**!

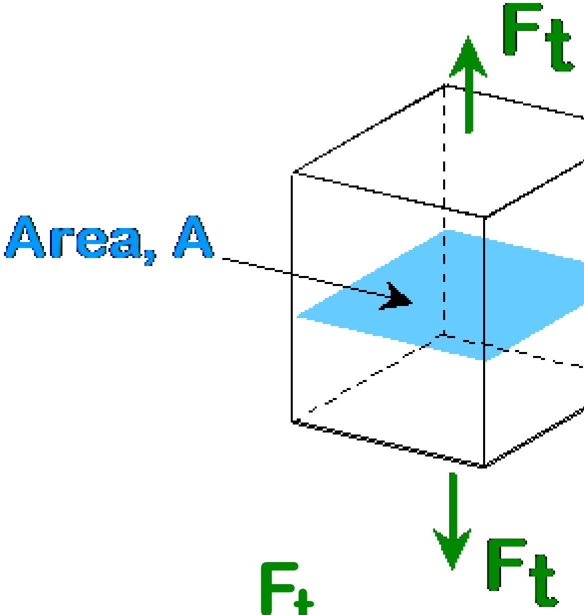
PLASTIC DEFORMATION (METALS)



Plastic means **permanent**!

ENGINEERING STRESS

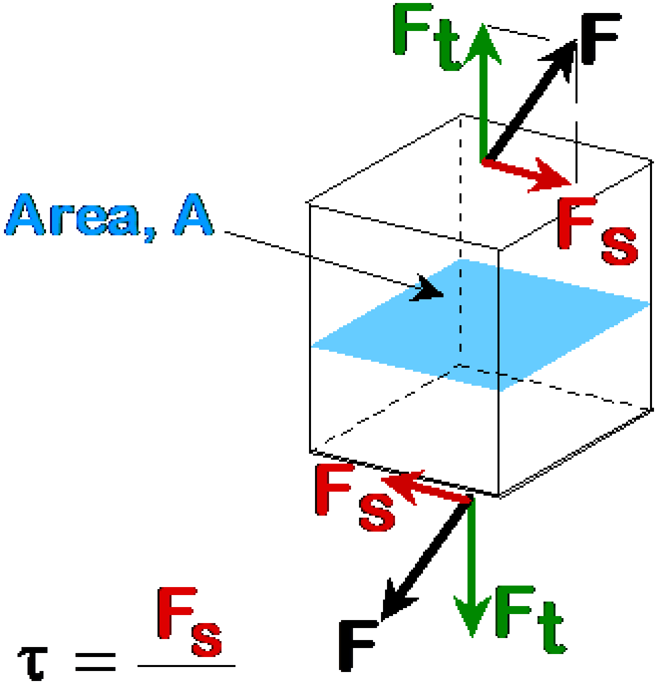
- **Tensile** stress, σ:



$$\sigma = \frac{F_t}{A_o}$$

original area before loading

- **Shear** stress, τ:



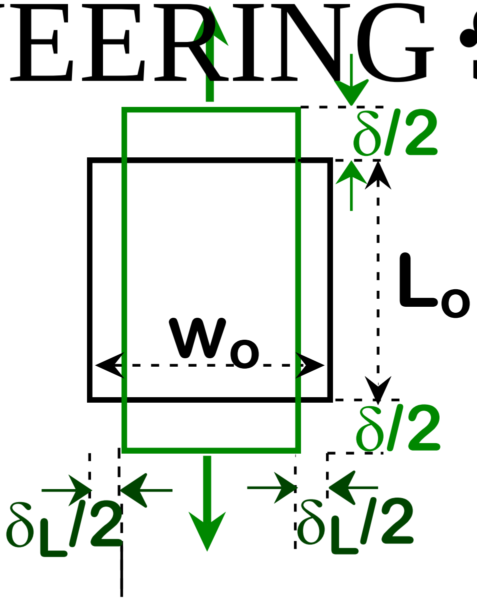
$$\tau = \frac{F_s}{A_o}$$

Stress has units:
N/m^2 or lb/in^2

ENGINEERING STRAIN

- **Tensile** strain:

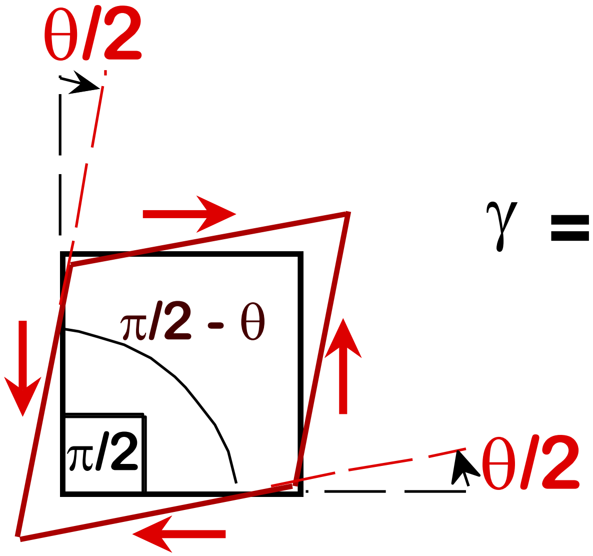
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral** strain:

$$\varepsilon_L = \frac{-\delta_L}{w_o}$$

- **Shear** strain:

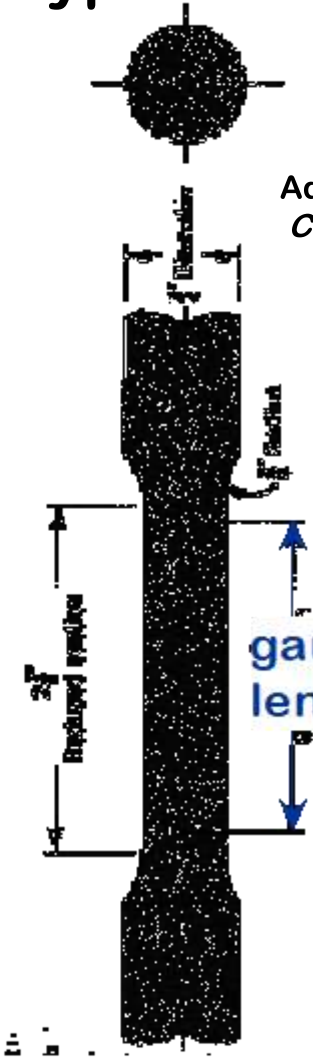


$$\gamma = \tan \theta$$

Strain is always dimensionless.

STRESS-STRAIN TESTING

- **Typical tensile specimen**

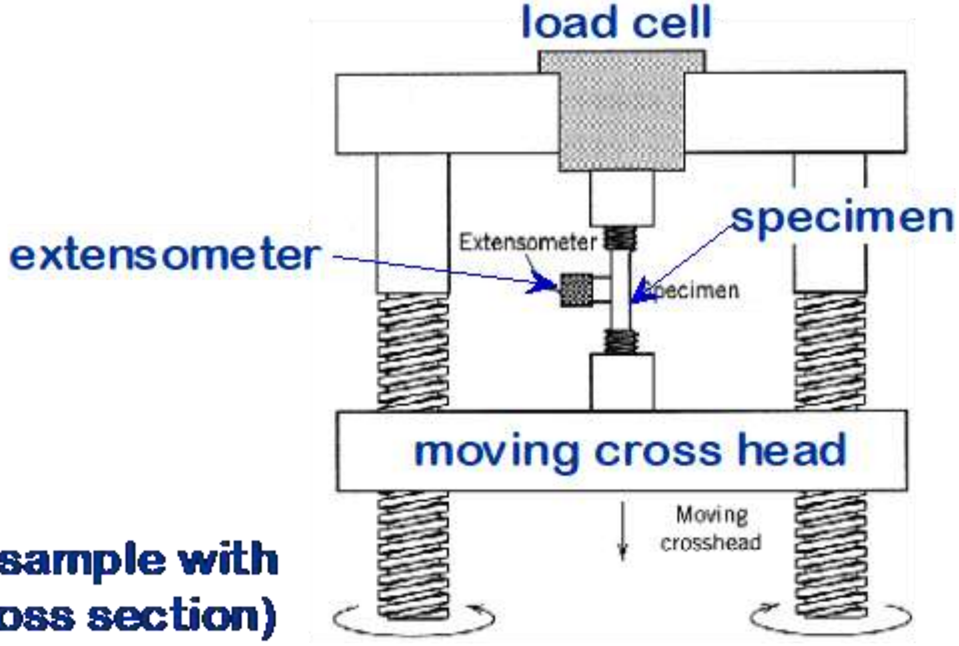


Adapted from Fig. 6.2, *Callister 6e.*

gauge length = (portion of sample with reduced cross section)

- **Other types of tests:**
  - **--compression: brittle materials (e.g., concrete)**
  - **--torsion: cylindrical tubes, shafts.**

- **Typical tensile test machine**



load cell

extensometer

specimen

moving cross head

Adapted from Fig. 6.3, *Callister 6e.* (Fig. 6.3 is taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

LINEAR ELASTIC PROPERTIES

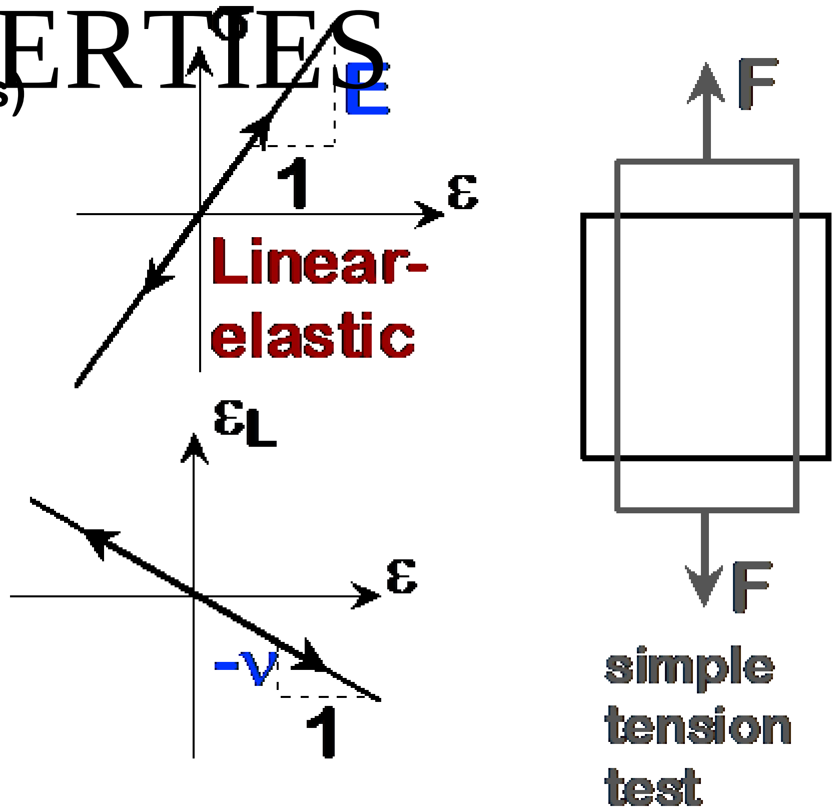
- **Modulus of Elasticity, E:**
  (also known as Young's modulus)
- **Hooke's Law**:

$$\sigma = E\,\varepsilon$$

- **Poisson's ratio, ν**:

$$\nu = -\frac{\varepsilon_L}{\varepsilon}$$

metals: ν ~ 0.33
ceramics: ~0.25
polymers: ~0.40

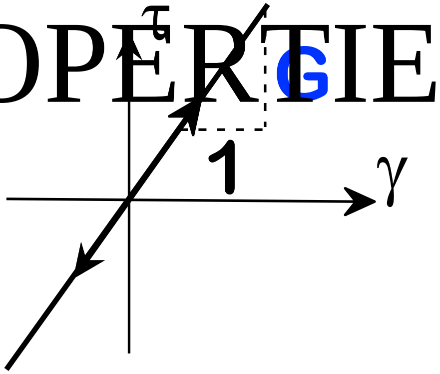


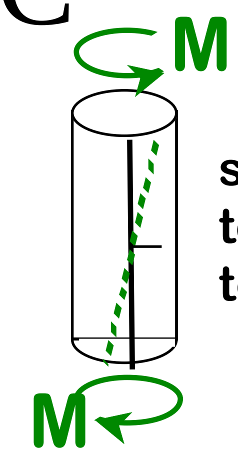
Units:
E: [GPa] or [psi]
ν: dimensionless

OTHER ELASTIC PROPERTIES

- Elastic **Shear modulus, G:**

$$\tau = G\,\gamma$$

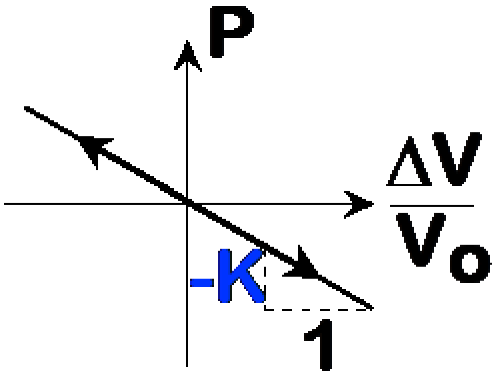


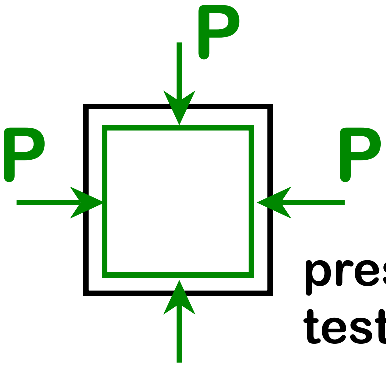


simple torsion test

- Elastic **Bulk modulus, K:**

$$P = -K\frac{\Delta V}{V_o}$$



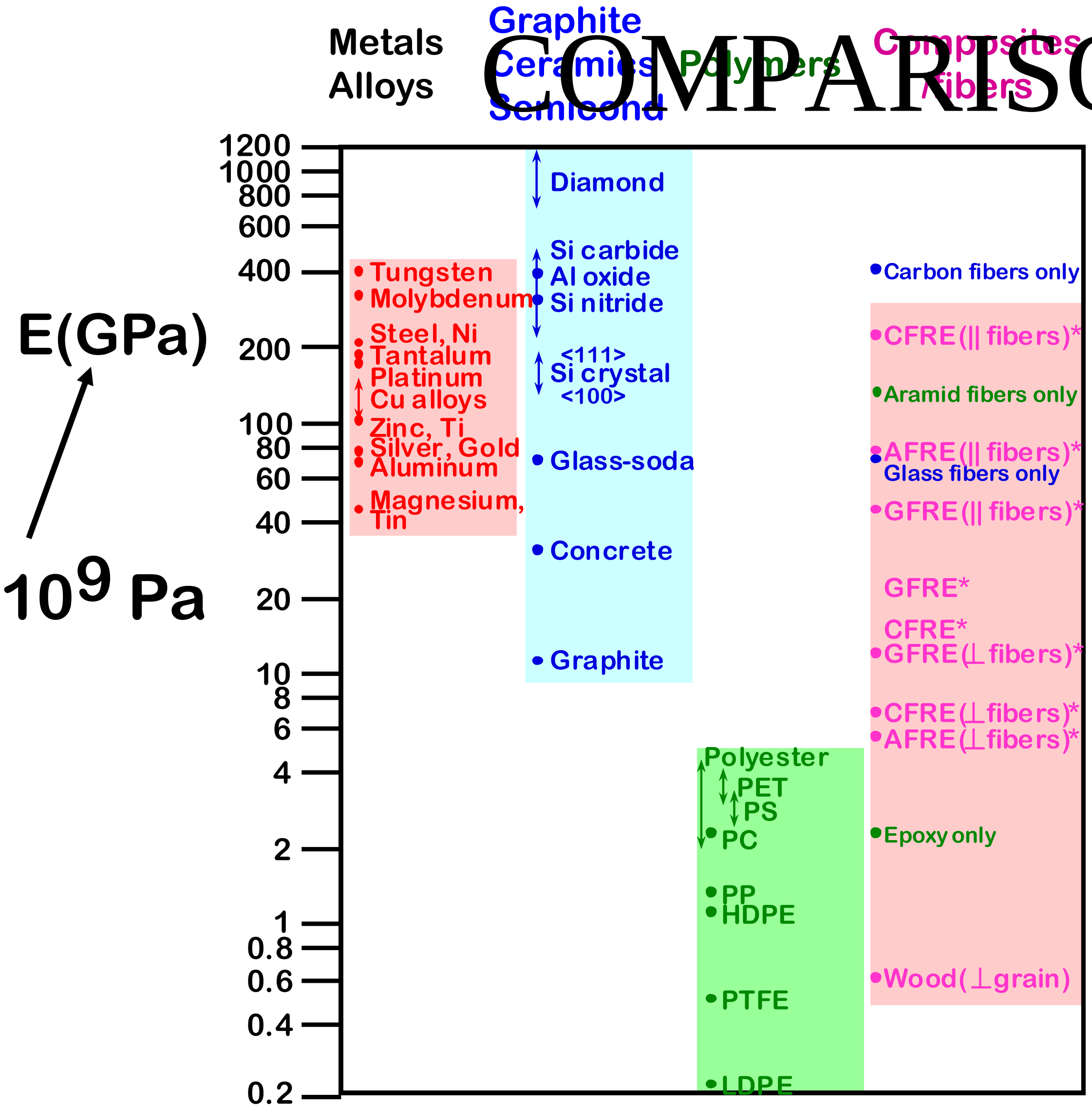


pressure test: Init. vol $=V_o$. Vol chg. $= \Delta V$

- Special relations for isotropic materials:

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)}$$

YOUNG'S MODULI: COMPARISON



$E_{ceramics}$

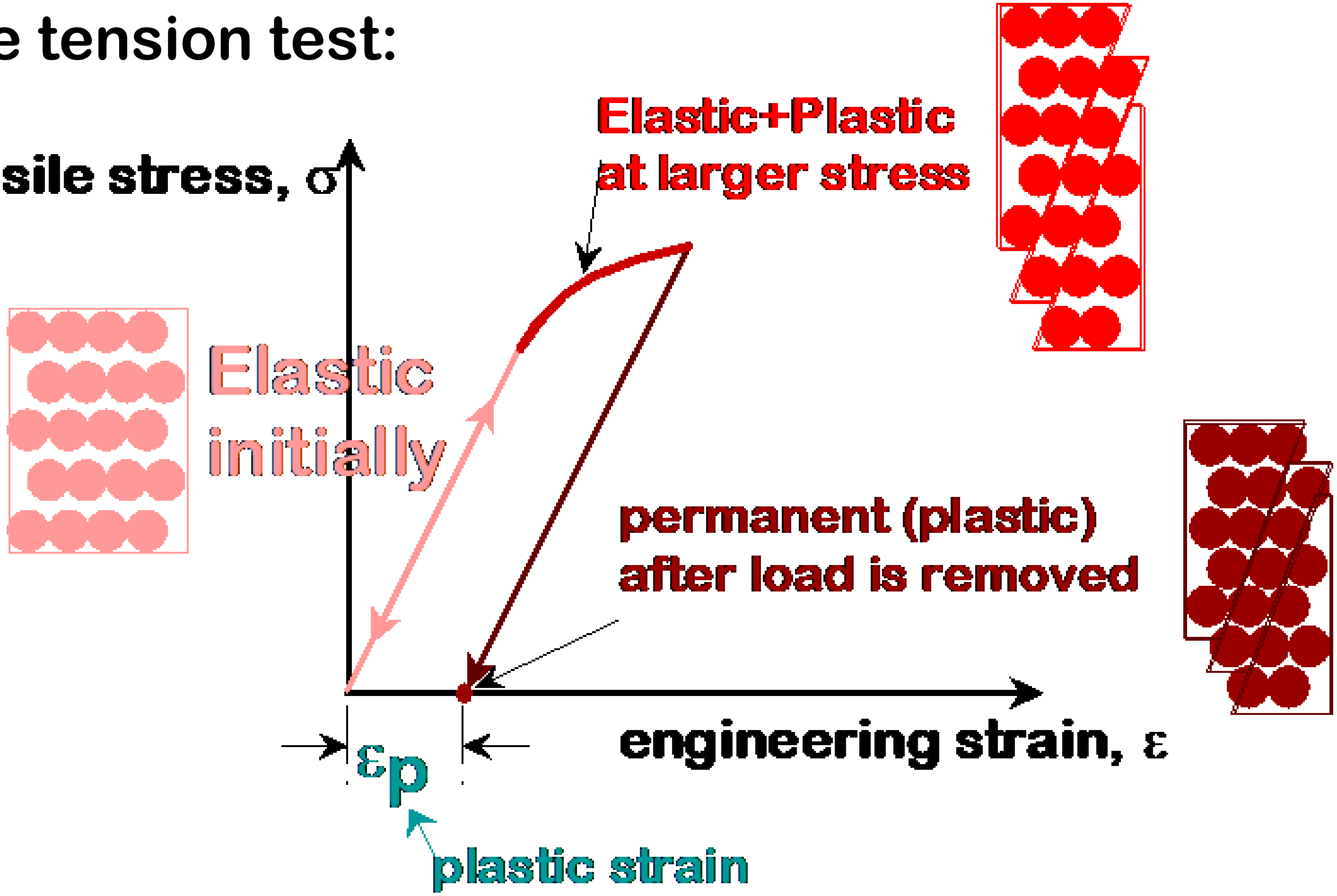
$> E_{metals}$

$>> E_{polymers}$

PLASTIC (PERMANENT) DEFORMATION

(at lower temperatures, $T < T_{melt}/3$)

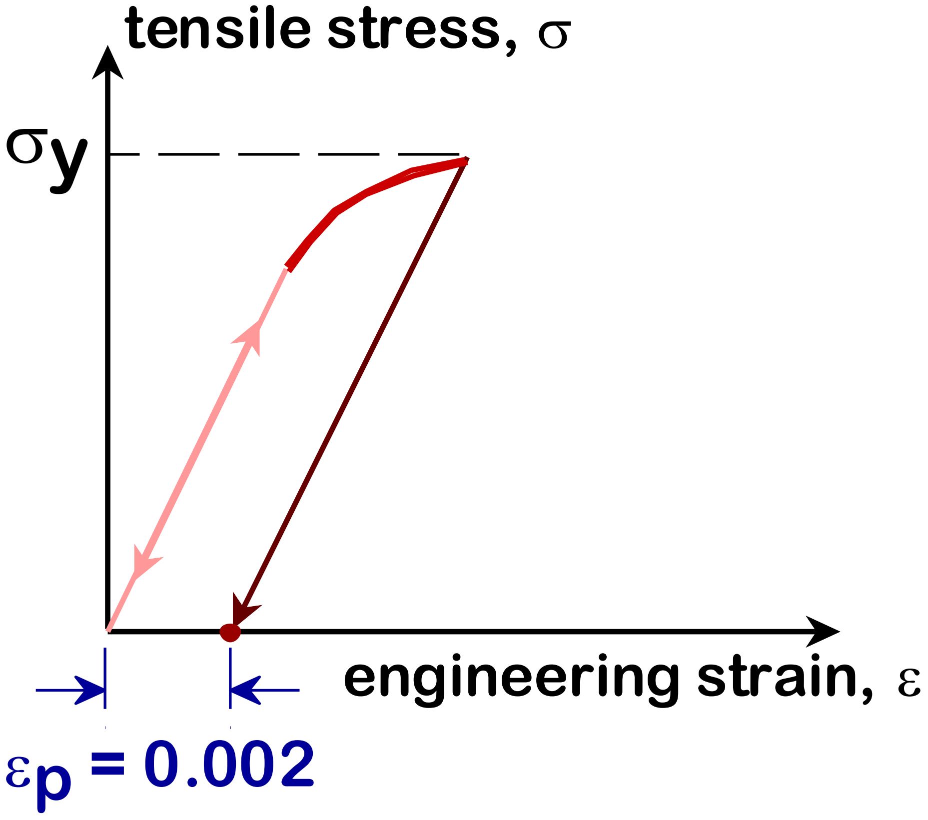
- **Simple tension test:**



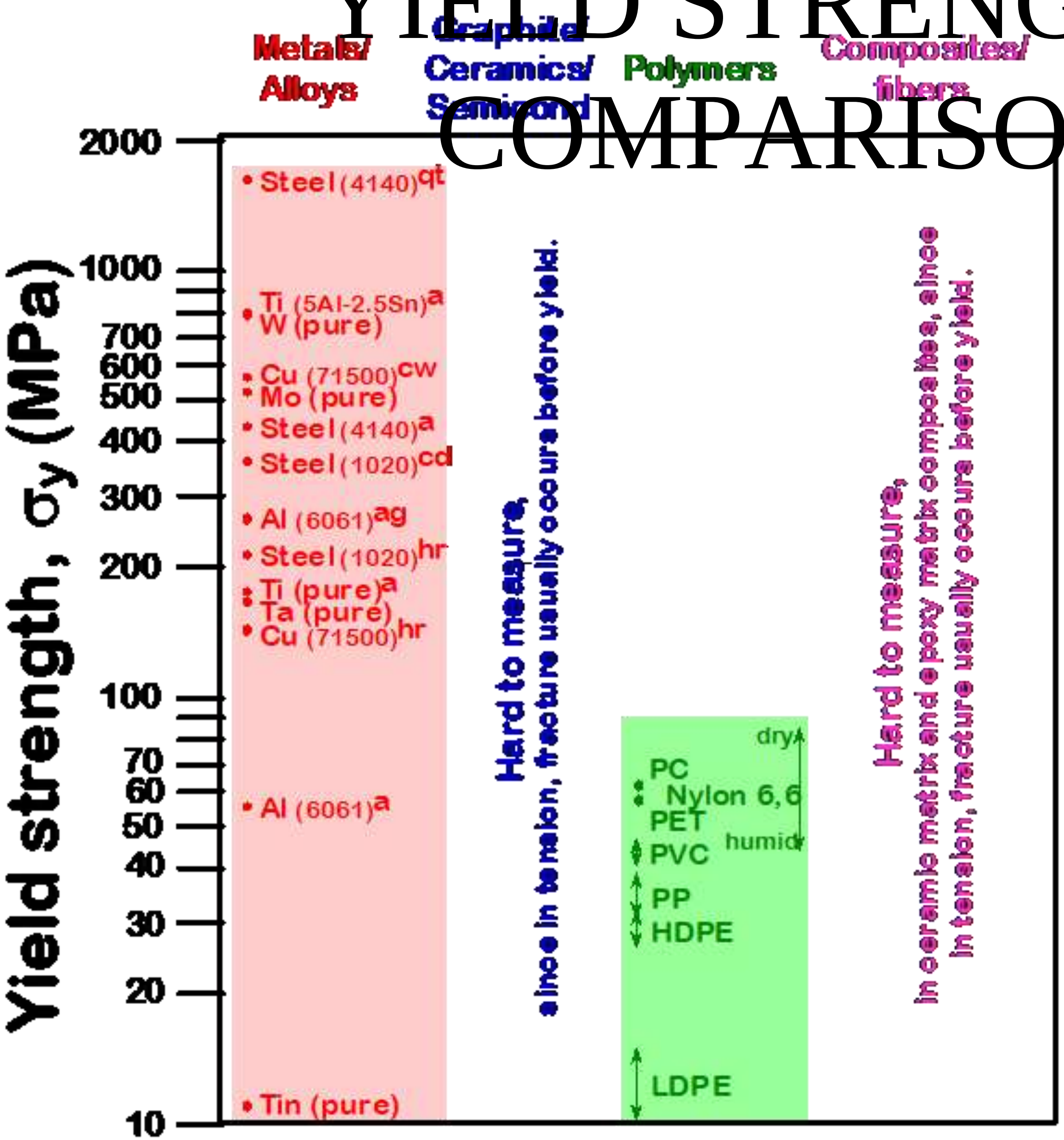
YIELD STRENGTH, σ_y

- Stress at which *noticeable* plastic deformation has occurred.

when $\varepsilon_p = 0.002$



YIELD STRENGTH: COMPARISON



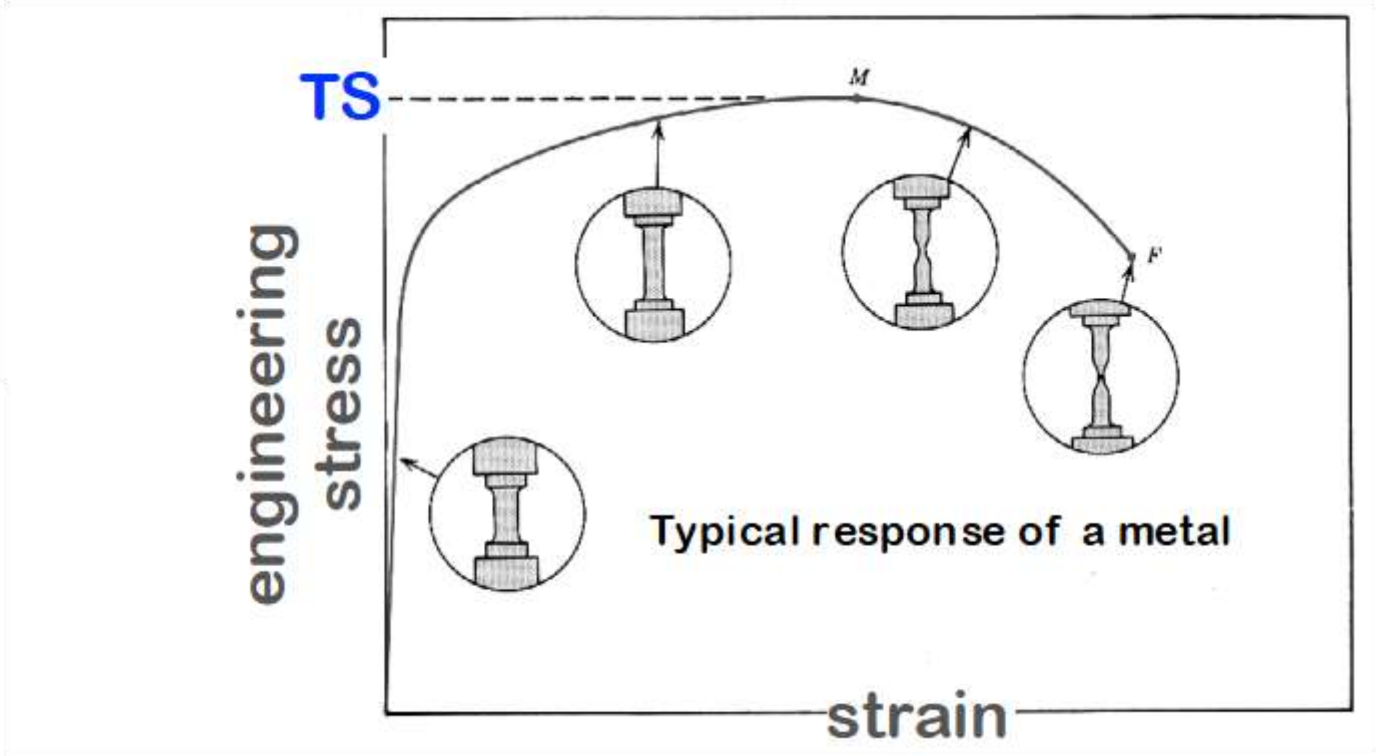
σ_y(ceramics)
$>>\sigma_y$(metals)
$>> \sigma_y$(polymers)

Room T values

Based on data in Table B4, *Callister 6e*.
a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

TENSILE STRENGTH, TS

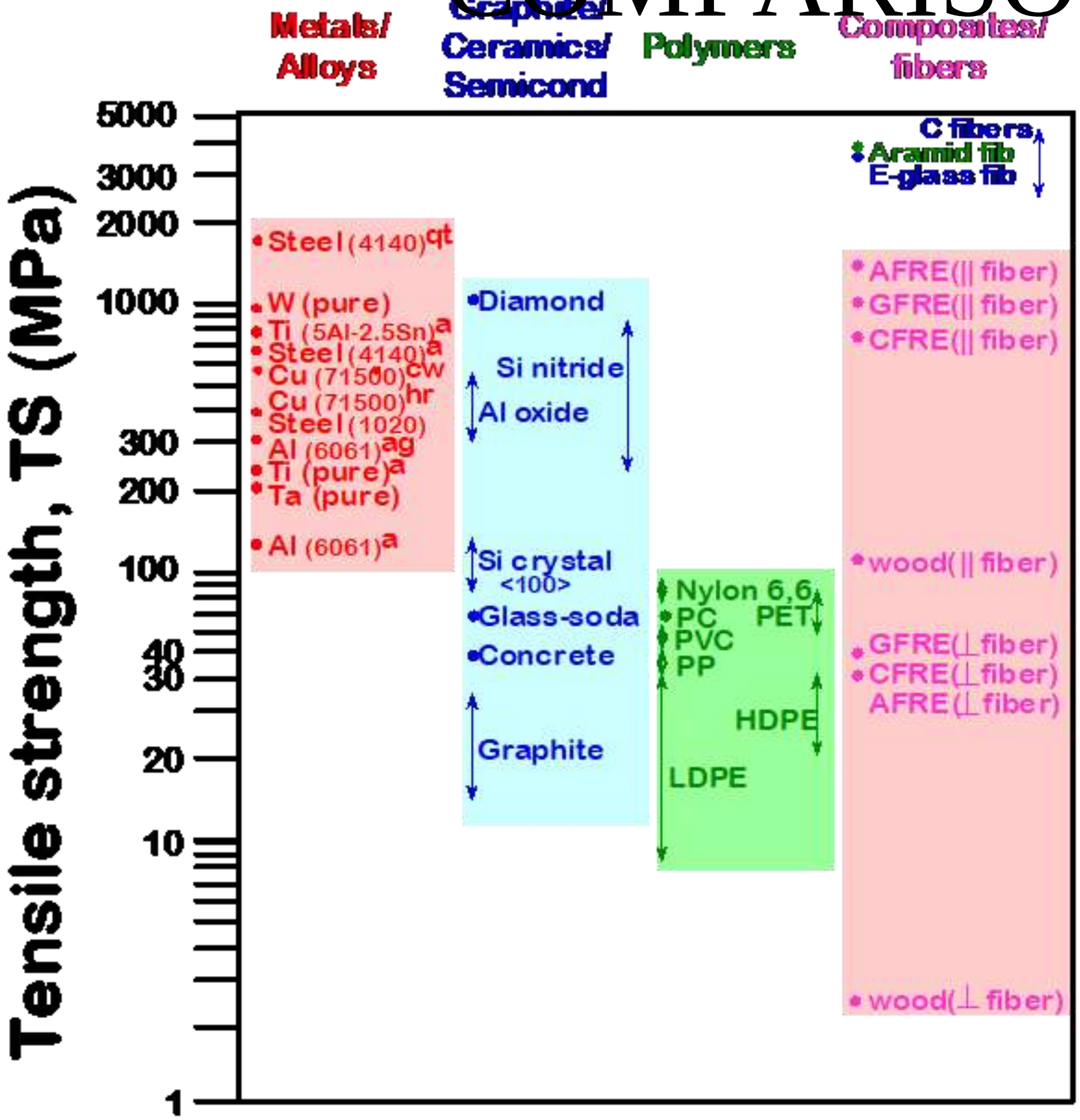
- **Maximum possible engineering stress in tension.**



Adapted from Fig. 6.11, *Callister 6e.*

- **Metals:** occurs when noticeable necking starts.
- **Ceramics:** occurs when crack propagation starts.
- **Polymers:** occurs when polymer backbones are aligned and about to break.

TENSILE STRENGTH: COMPARISON



$\mathrm{TS}_{(ceram)}$

$\sim\mathrm{TS}_{(met)}$

$\sim\mathrm{TS}_{(comp)}$

$>>\mathrm{TS}_{(poly)}$

Room T values

Based on data in Table B4, *Callister 6e*.

a = annealed

hr = hot rolled

ag = aged

cd = cold drawn

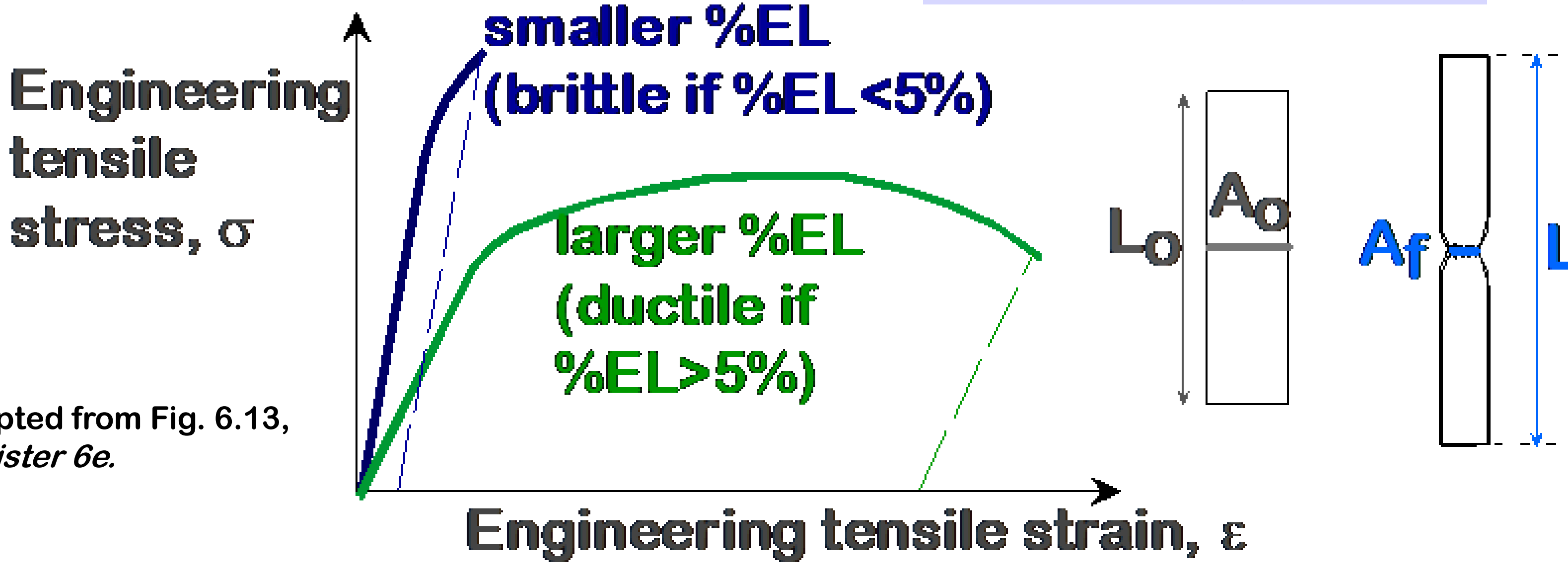
cw = cold worked

qt = quenched & tempered

AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

DUCTILITY, %EL

- **Plastic tensile strain at failure:** $$\%EL = \frac{L_f - L_o}{L_o} \times 100$$

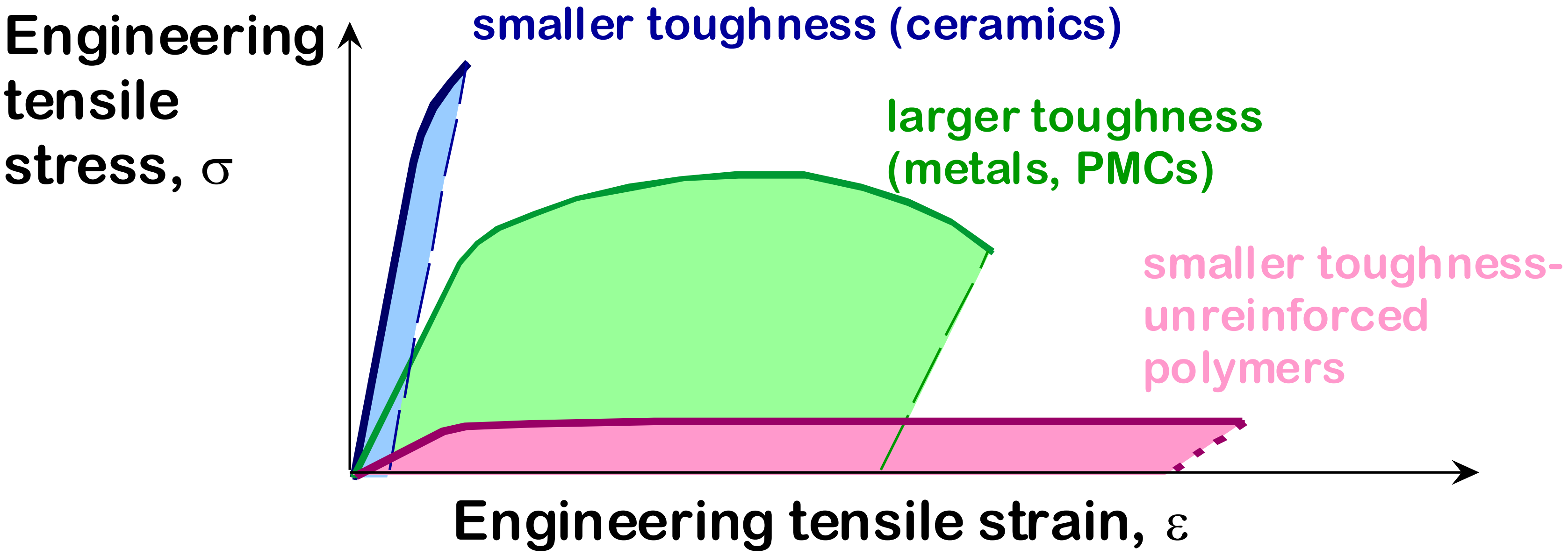


Adapted from Fig. 6.13, *Callister 6e.*

- **Another ductility measure:** $$\%AR = \frac{A_o - A_f}{A_o} \times 100$$
- **Note: %AR and %EL are often comparable.**
  --Reason: crystal slip does not change material volume.
  --%AR > %EL possible if internal voids form in neck.

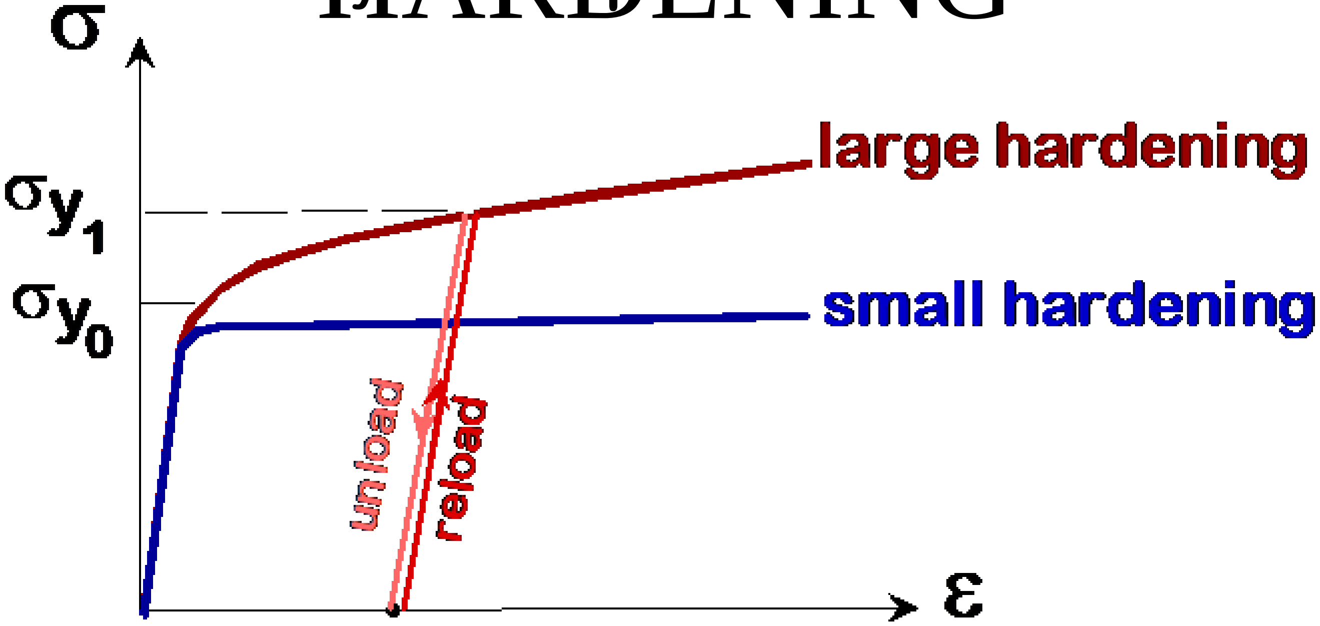
TOUGHNESS

- **Energy to break a unit volume of material**
- **Approximate by the area under the stress-strain curve.**



HARDENING

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = C\left(\varepsilon_T\right)^n$$

hardening exponent:
n=0.15 (some steels)
to n=0.5 (some copper)

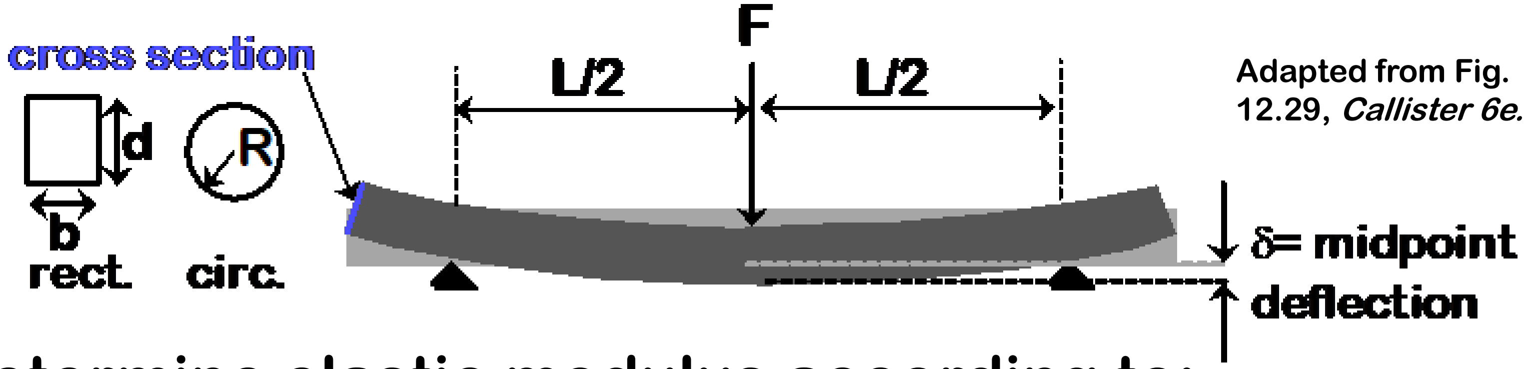
"true" stress (F/A)

"true" strain: $\ln(L/L_o)$

MEASURING ELASTIC MODULUS

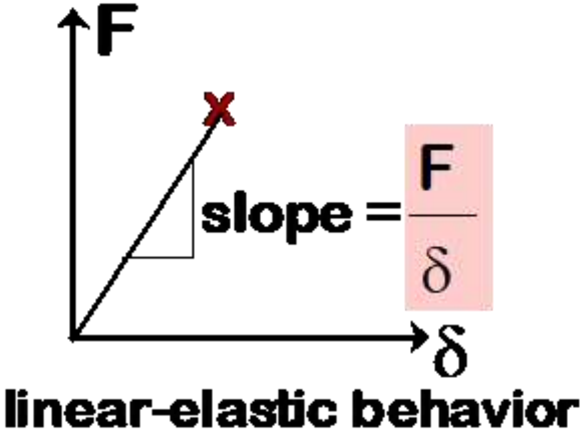
- **Room T behavior is usually elastic, with brittle failure.**
- **3-Point Bend Testing often used.**

--tensile tests are difficult for brittle materials.



Adapted from Fig. 12.29, *Callister 6e.*

- **Determine elastic modulus according to:**



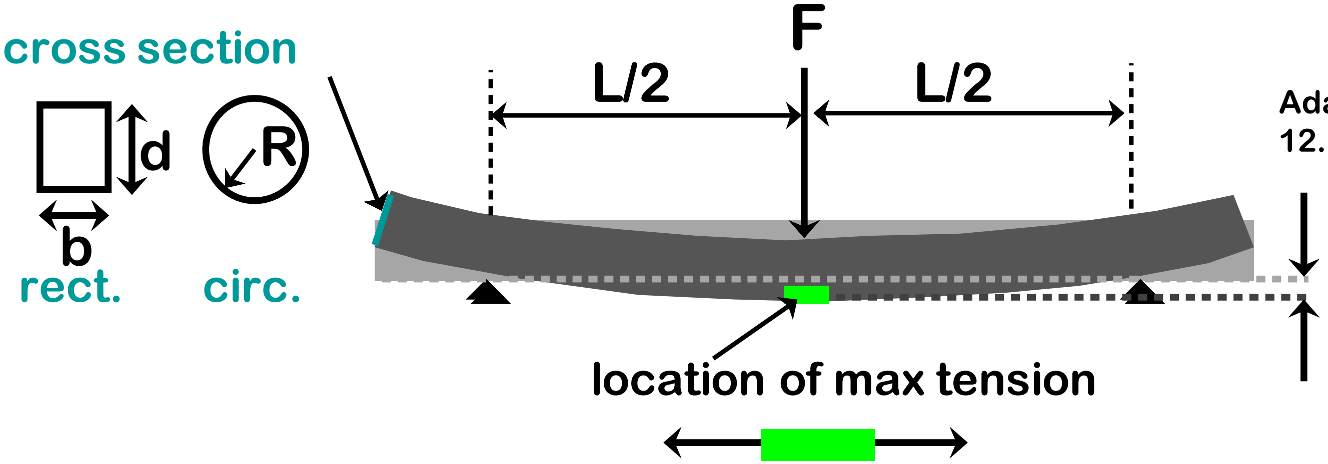
$$E = \frac{F}{\delta}\frac{L^3}{4bd^3} = \frac{F}{\delta}\frac{L^3}{12\pi R^4}$$

rect. cross section

circ. cross section

MEASURING STRENGTH

- 3-point bend test to measure room T strength.

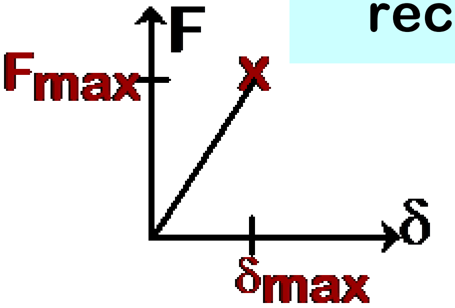


Adapted from Fig. 12.29, *Callister 6e.*

- Flexural strength:

$$\sigma_{fs} = \sigma_m^{fail} = \frac{1.5 F_{max} L}{b d^2} = \frac{F_{max} L}{\pi R^3}$$

rect.

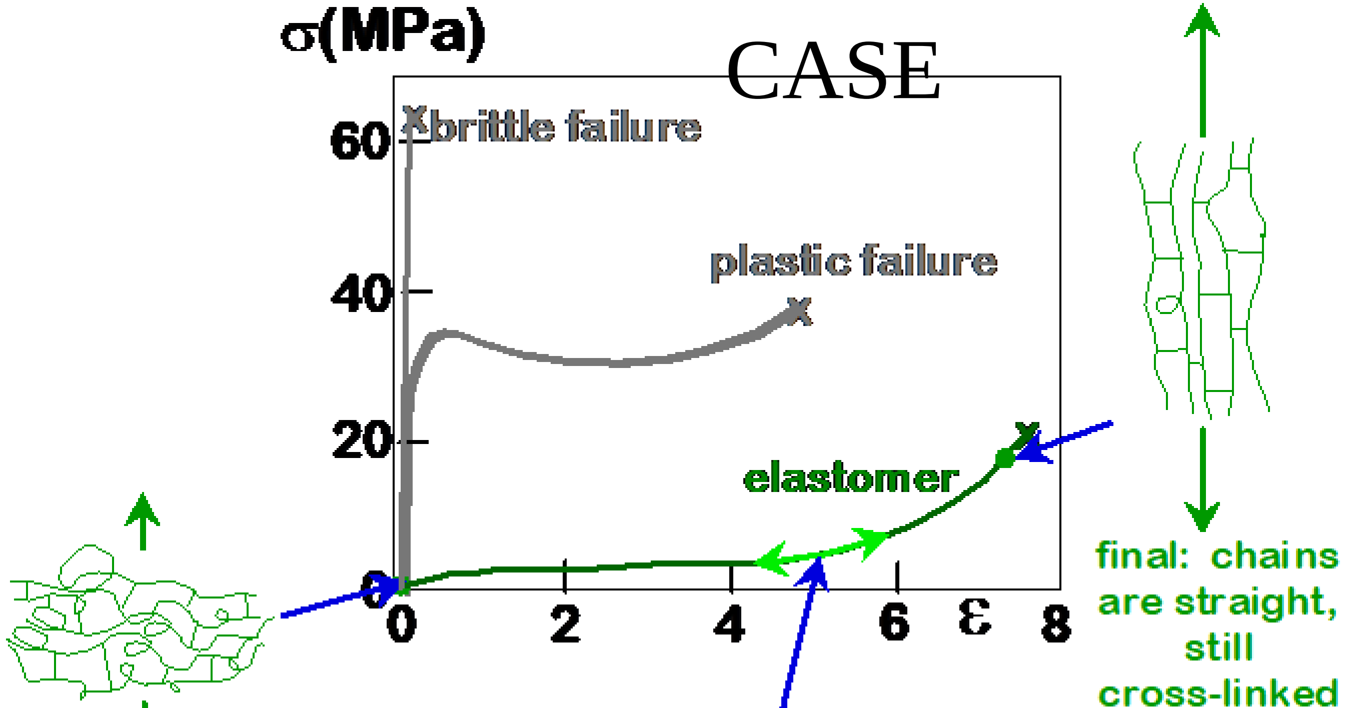


- Typ. values:

Material	σ_{fs}(MPa)	E(GPa)
Si nitride	700-1000	300
Si carbide	550-860	430
Al oxide	275-550	390
glass (soda)	69	69

Data from Table 12.5, *Callister 6e.*

TENSILE RESPONSE: ELASTOMER CASE



initial: amorphous chains are kinked, heavily cross-linked.

Deformation is reversible!

final: chains are straight, still cross-linked

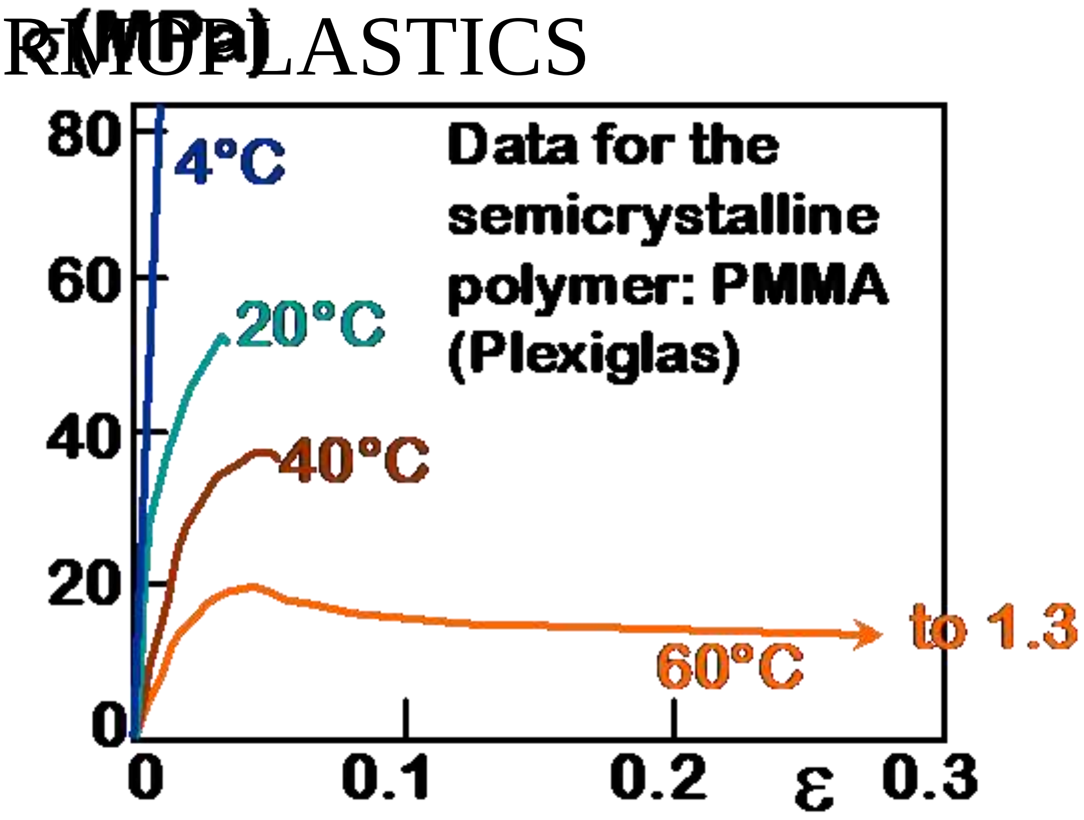
Stress-strain curves adapted from Fig. 15.1, *Callister 6e.* Inset figures along elastomer curve (green) adapted from Fig. 15.14, *Callister 6e*. (Fig. 15.14 is from Z.D. Jastrzebski, *The Nature and Properties of Engineering Materials*, 3rd ed., John Wiley and Sons, 1987.)

- **Compare to responses of other polymers:**
  --brittle response (aligned, cross linked & networked case)
  --plastic response (semi-crystalline case)

T AND STRAIN RATE: THERMOPLASTICS

- **Decreasing T...**
  - **--increases E**
  - **--increases TS**
  - **--decreases %EL**

- **Increasing strain rate...**
  - **--same effects as decreasing T.**



Data for the semicrystalline polymer: PMMA (Plexiglas)

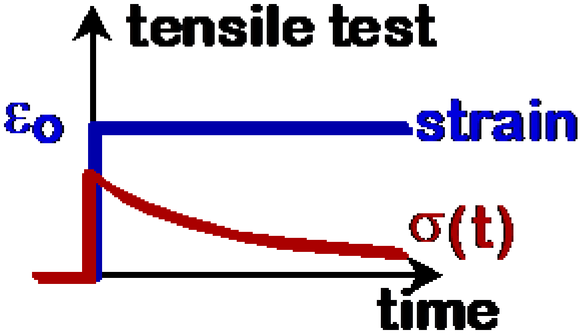
Adapted from Fig. 15.3, *Callister 6e*. (Fig. 15.3 is from T.S. Carswell and J.K. Nason, 'Effect of Environmental Conditions on the Mechanical Properties of Organic Plastics", *Symposium on Plastics*, American Society for Testing and Materials, Philadelphia, PA, 1944.)

TIME DEPENDENT DEFORMATION

- **Stress relaxation test**:

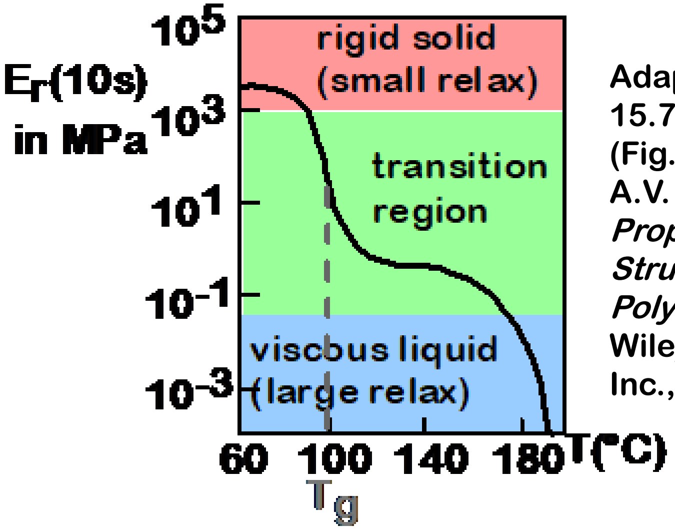
--strain to ε_o and hold.

--observe decrease in stress with time.



- Data: Large drop in E_r for $T > T_g$.

(amorphous polystyrene)



Adapted from Fig. 15.7, *Callister 6e*. (Fig. 15.7 is from A.V. Tobolsky, *Properties and Structures of Polymers*, John Wiley and Sons, Inc., 1960.)

- **Relaxation modulus**:

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_o}$$

- Sample T_g(C) values:

PE (low M_w)	-110
PE (high M_w)	- 90
PVC	+ 87
PS	+100
PC	+150

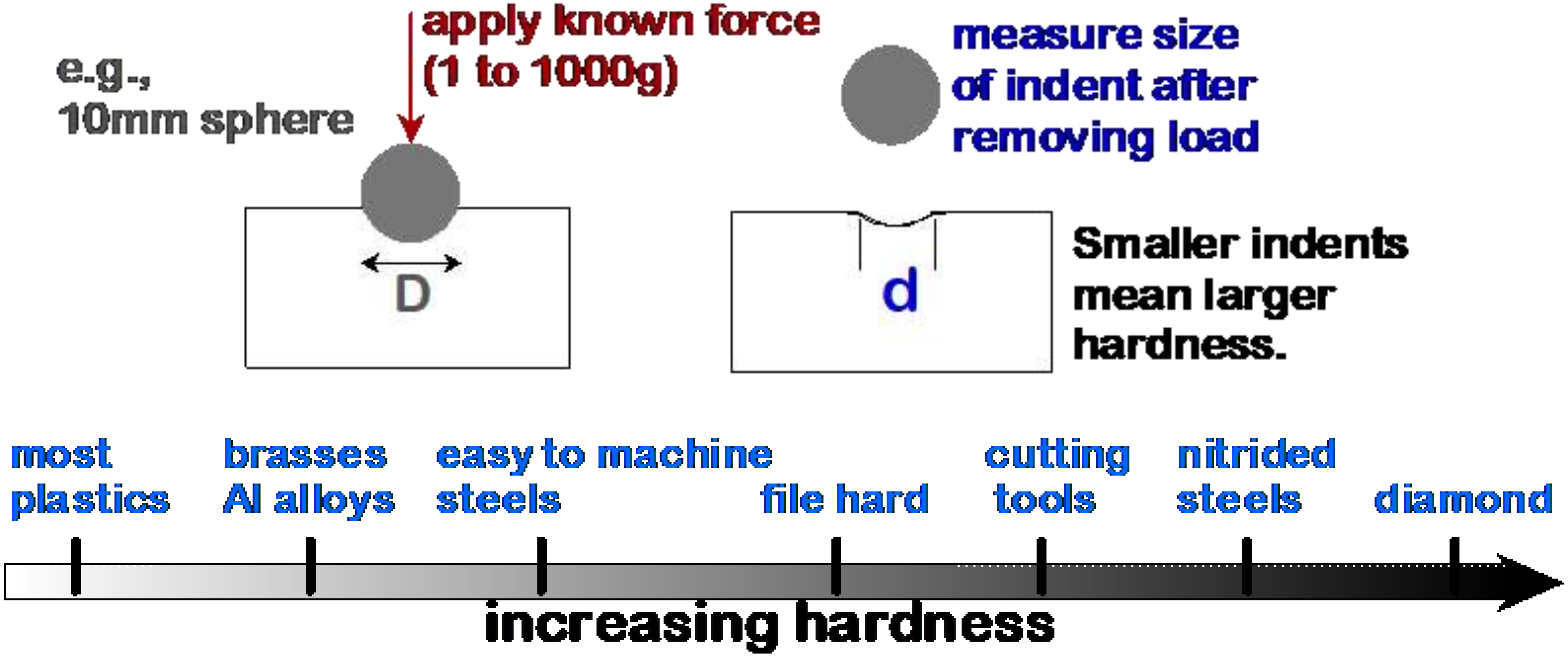
Selected values from Table 15.2, *Callister 6e*.

HARDNESS

- **Resistance to permanently indenting the surface.**
- **Large hardness means:**

  --resistance to plastic deformation or cracking in compression.

  --better wear properties.



Adapted from Fig. 6.18, *Callister 6e.* (Fig. 6.18 is adapted from G.F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202, John Wiley and Sons, 1957.)

DESIGN OR SAFETY FACTORS

- **Design uncertainties mean we do not push the limit.**
- **Factor of safety, N**

$$\sigma_{working} = \frac{\sigma_y}{\boxed{N}}$$

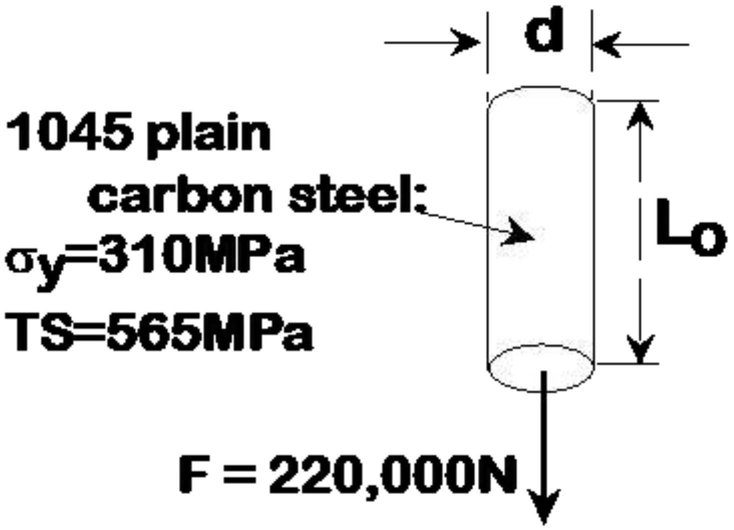
Often N is between 1.2 and 4

- **Ex: Calculate a diameter, d, to ensure that yield does not occur in the 1045 carbon steel rod below. Use a factor of safety of 5.**

$$\boxed{\sigma_{working}} = \frac{\sigma_y}{\boxed{N}}$$

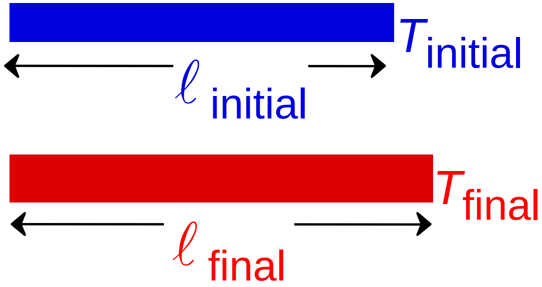
$$\boxed{\frac{220{,}000\text{N}}{\pi\left(d^2/4\right)}}$$

5



Thermal Expansion

Materials change size when temperature is changed

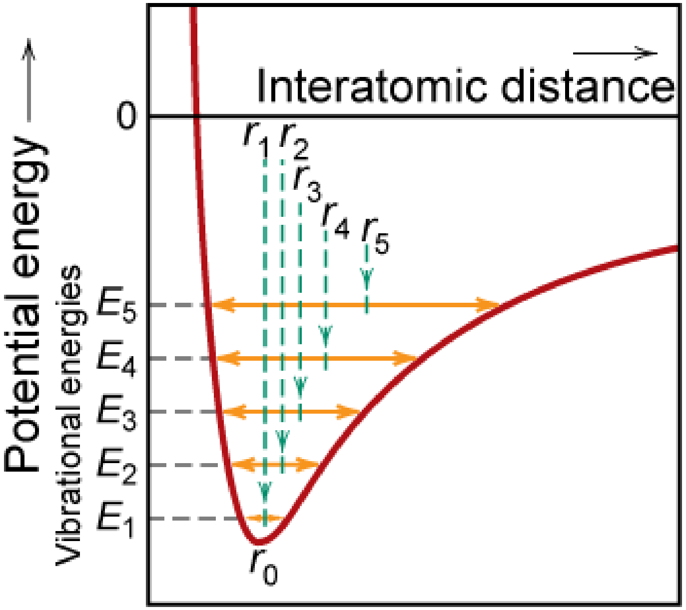


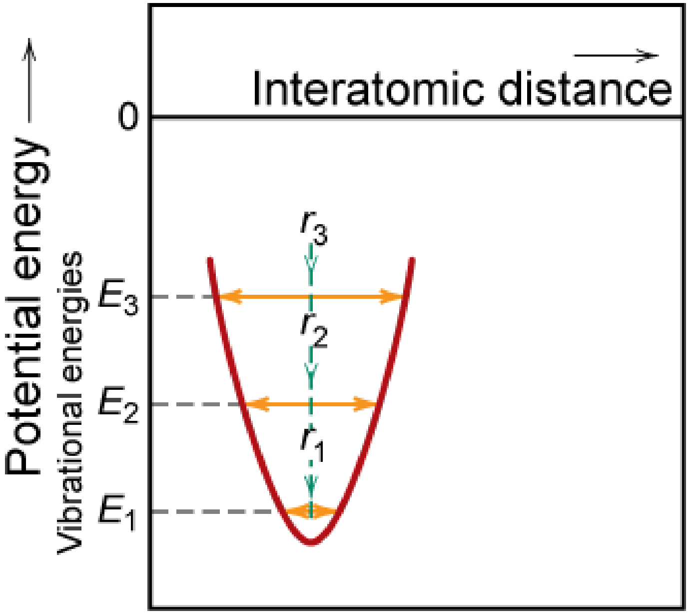
$T_{\text{final}} > T_{\text{initial}}$

$$\frac{\ell_{\text{final}} - \ell_{\text{initial}}}{\ell_{\text{initial}}} = \alpha_{\ell}\left(T_{\text{final}} - T_{\text{initial}}\right)$$

linear coefficient of thermal expansion (1/K or 1/°C)

Atomic Perspective: Thermal Expansion





Asymmetric curve:
- -- increase temperature,
- -- increase in interatomic separation
- -- thermal expansion

Symmetric curve:
- -- increase temperature,
- -- no increase in interatomic separation
- -- no thermal expansion

Coefficient of Thermal Expansion: Comparison

Material	α_ℓ (10^{-6}/°C) at room *T*
• <u>Polymers</u>	
Polypropylene	145-180
Polyethylene	106-198
Polystyrene	90-150
Teflon	126-216
• <u>Metals</u>	
Aluminum	23.6
Steel	12
Tungsten	4.5
Gold	14.2
• <u>Ceramics</u>	
Magnesia (MgO)	13.5
Alumina (Al_2O_3)	7.6
Soda-lime glass	9
Silica (cryst. SiO_2)	0.4

Polymers have larger α_ℓ values because of weak secondary bonds

- **Q: Why does α_ℓ generally decrease with increasing bond energy?**

Thermal Stresses

- Occur due to:
  - -- restrained thermal expansion/contraction
  - -- temperature gradients that lead to differential dimensional changes

Thermal stress $= \sigma$

$$= E\alpha_{\ell}(T_0 - T_f) = E\alpha_{\ell}\Delta T$$

SUMMARY

- **Stress** and **strain**: These are size-independent measures of load and displacement, respectively.
- **Elastic** behavior: This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus (E or G).
- **Plastic** behavior: This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches σy.
- **Toughness**: The energy needed to break a unit volume of material.
- **Ductility**: The plastic strain at failure.

Note: For materials selection cases related to mechanical behavior, see slides 20-4 to 20-10.

HEAT TREATMENT

HEAT TREATMENT

With focus on Steels

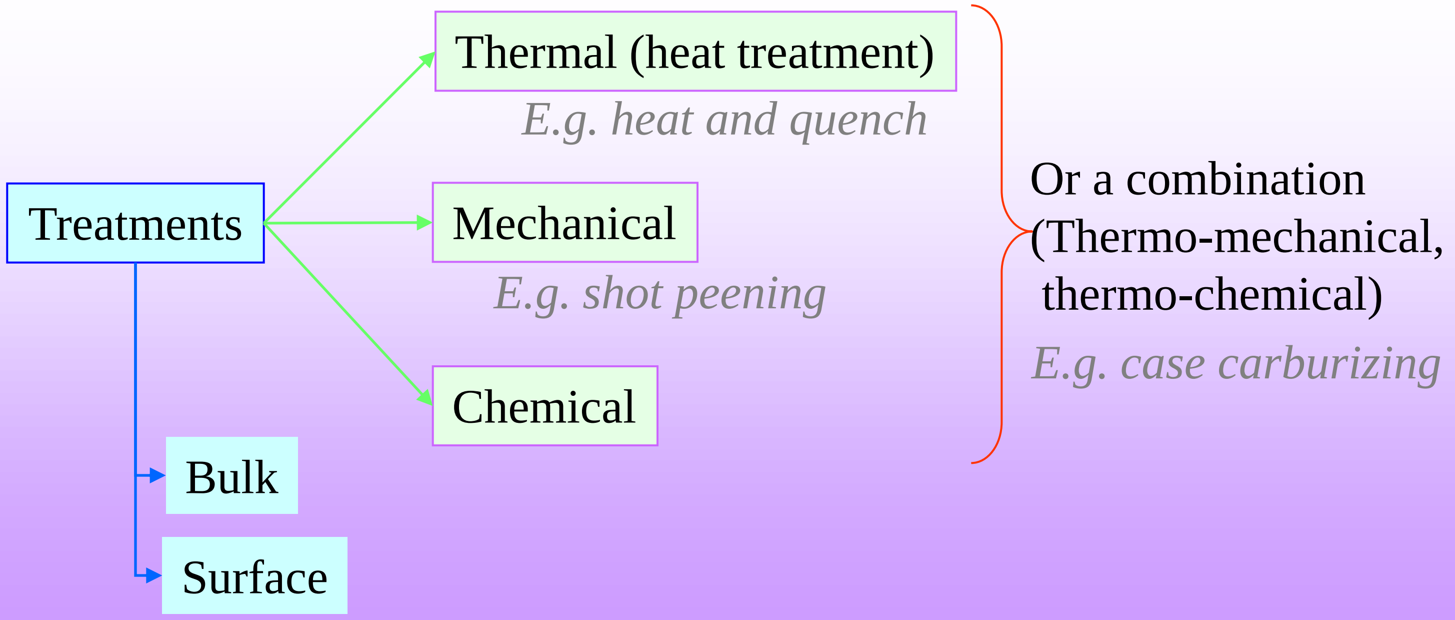
- ❑ Bulk and Surface Treatments
- ❑ Annealing, Normalizing, Hardening, Tempering
- ❑ Hardenability

Principles of Heat Treatment of Steels
Romesh C Sharma
New Age International (P) Ltd., Publishers, New Delhi, 1993.

Heat Treatment of Steels

Click here to revise the basics required for this topic: Phase_Transformations

- We have noted that how TTT and CCT diagrams can help us design heat treatments to design the microstructure of steels and hence engineer the properties. In some cases a gradation in properties may be desired (usually from the surface to the interior- a hard surface with a ductile/tough interior/bulk).
- In general three kinds of treatments are: (i) Thermal (heat treatment), (ii) Mechanical (working), (iii) Chemical (alteration of composition). A combination of these treatments are also possible (e.g. thermo-mechanical treatments, thermo-chemical treatments).
- The treatment may affect the whole sample or only the surface.
- A typical industrial treatment cycle may be complicated with many steps (i.e. a combination of the simple steps which are outlined in the chapter).



Thermal (heat treatment)

E.g. heat and quench

Treatments

Mechanical

E.g. shot peening

Chemical

Bulk

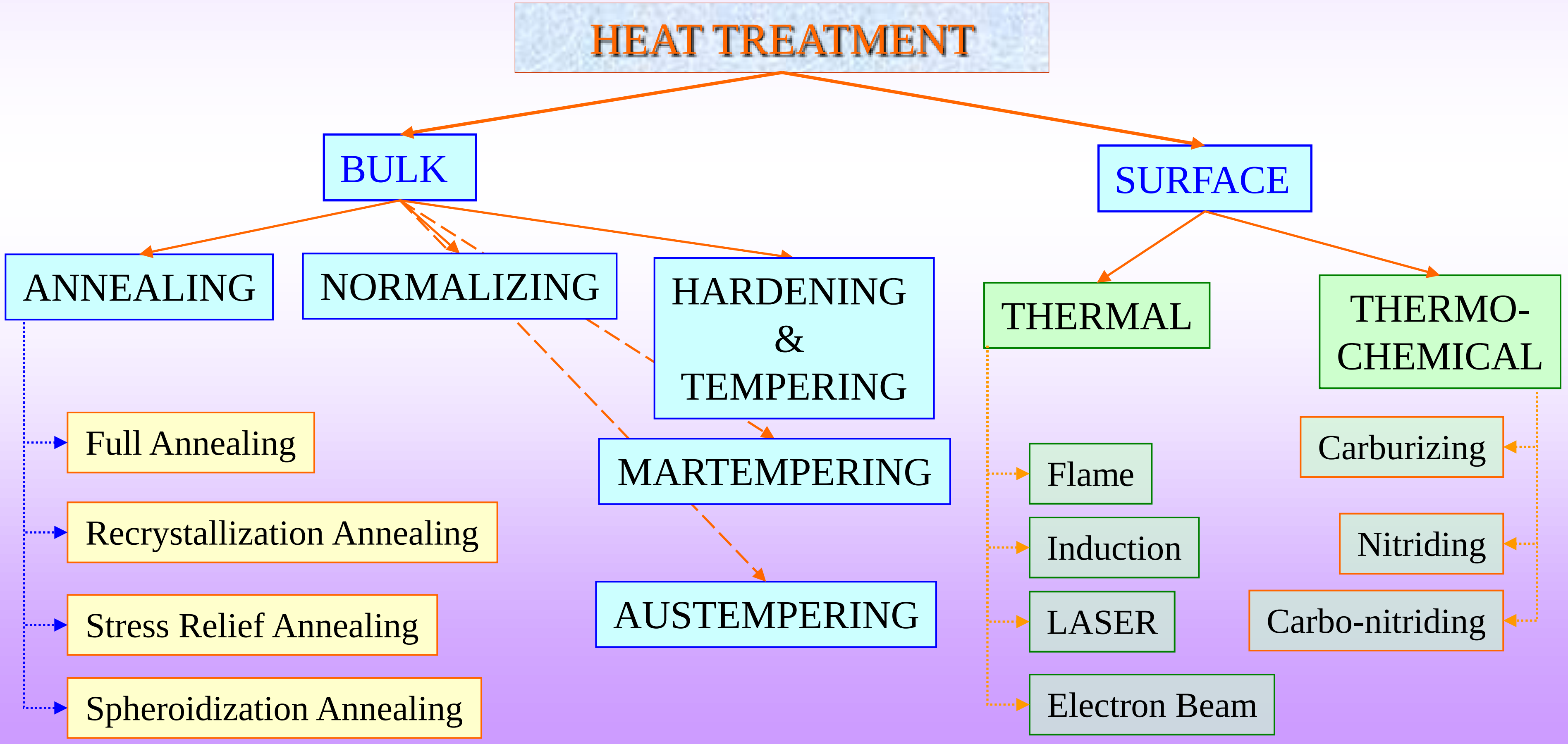
Surface

Or a combination (Thermo-mechanical, thermo-chemical)

E.g. case carburizing

An overview of important heat treatments

- A broad classification of heat treatments possible are given below. Many more specialized treatments or combinations of these are possible.



HEAT TREATMENT

BULK

SURFACE

ANNEALING

NORMALIZING

HARDENING & TEMPERING

MARTEMPERING

AUSTEMPERING

Full Annealing

Recrystallization Annealing

Stress Relief Annealing

Spheroidization Annealing

THERMAL

THERMO-CHEMICAL

Flame

Induction

LASER

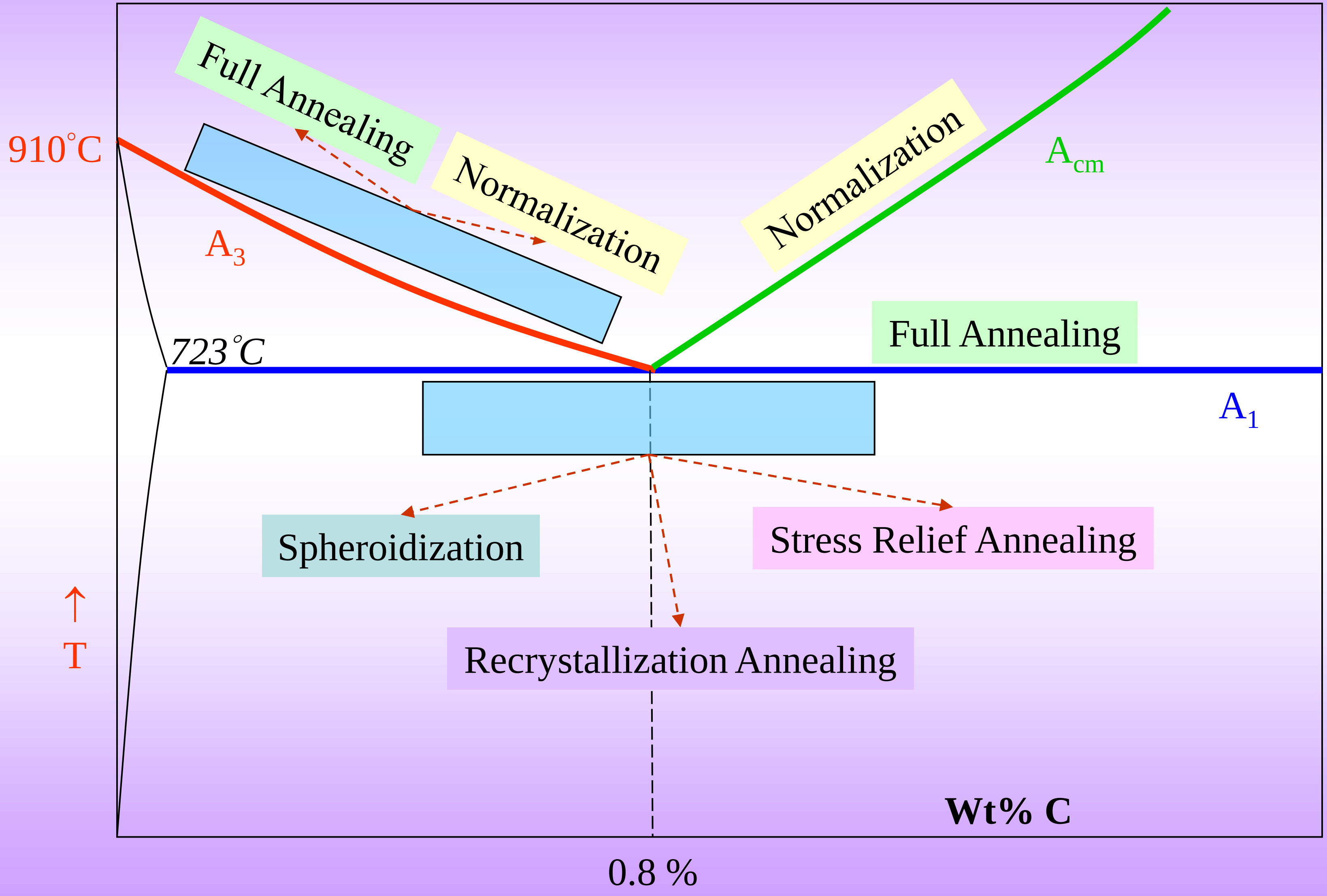
Electron Beam

Carburizing

Nitriding

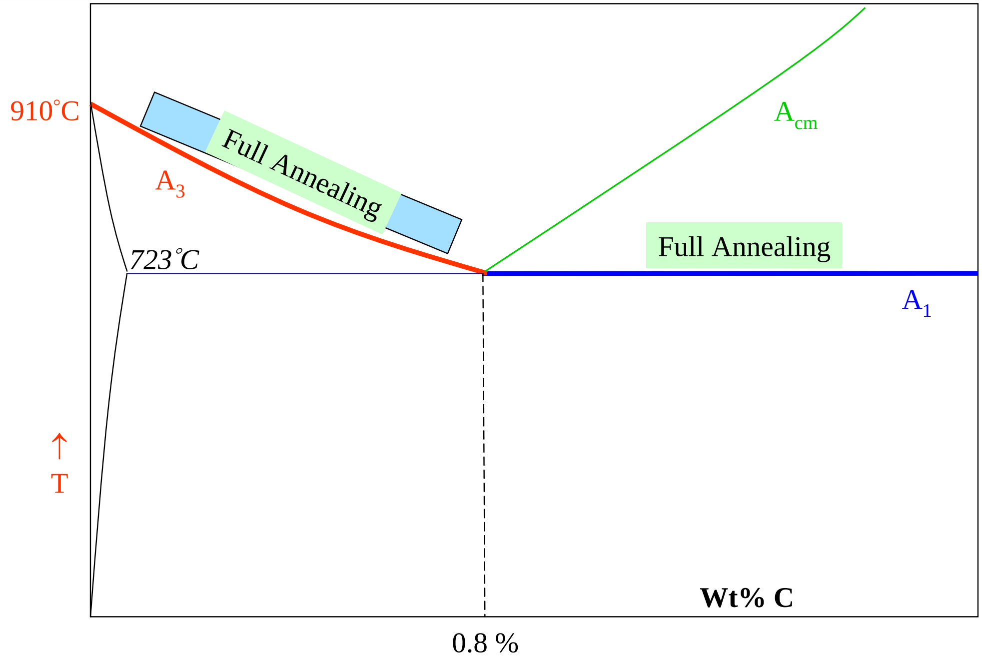
Carbo-nitriding

- Ranges of temperature where Annealing, Normalizing and Spheroidization treatment are carried out for hypo- and hyper-eutectoid steels.
- Details are in the coming slides.



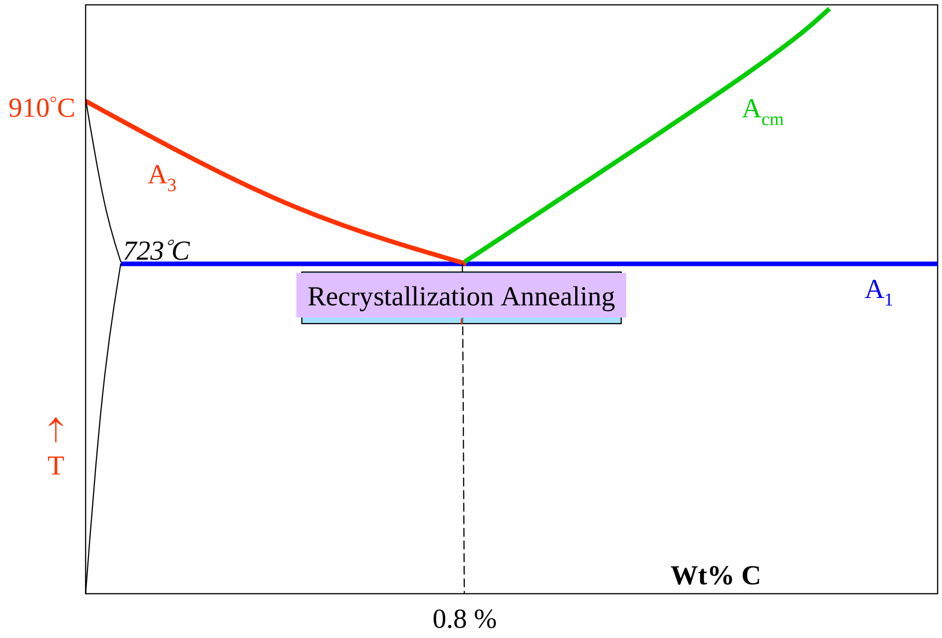
Full Annealing

- The purpose of this heat treatment is to obtain a material with high ductility. A microstructure with coarse pearlite (i.e. pearlite having high interlamellar spacing) is endowed with such properties.
- The range of temperatures used is given in the figure below.
- The steel is heated above A_3 (for hypo-eutectoid steels) & A_1 (for hyper-eutectoid steels) → (hold) → then the steel is furnace cooled to obtain Coarse Pearlite.
- Coarse Pearlite has low (↓) Hardness but high (↑) Ductility.
- For hyper-eutectoid steels the heating is not done above A_{cm} to avoid a continuous network of proeutectoid cementite along prior Austenite grain boundaries (presence of cementite along grain boundaries provides easy path for crack propagation).



Recrystallization Annealing

- During any cold working operation (say cold rolling), the material becomes harder (due to work hardening), but loses its ductility. This implies that to continue deformation the material needs to be recrystallized (wherein strain free grains replace the 'cold worked grains').
- Hence, recrystallization annealing is used as an intermediate step in (cold) deformation processing.
- To achieve this the sample is heated below A_1 and held there for sufficient time for recrystallization to be completed.



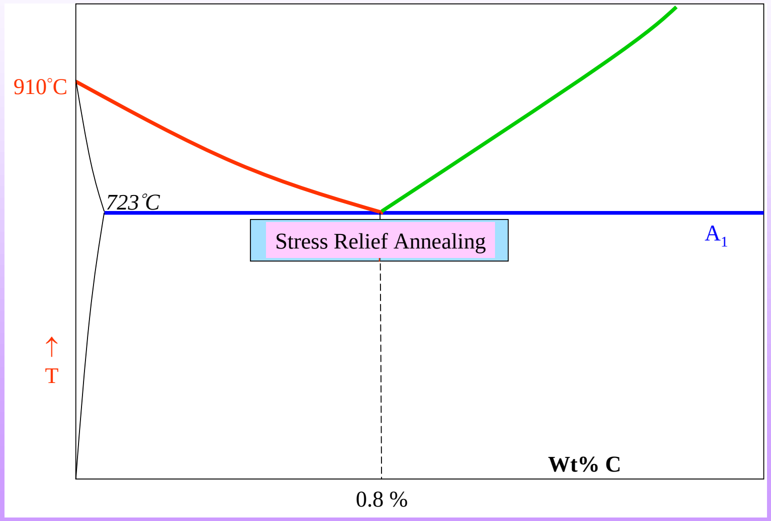
Stress Relief Annealing

- Due to various processes like quenching (differential cooling of surface and interior), machining, phase transformations (like martensitic transformation), welding, etc. the residual stresses develop in the sample. Residual stress can lead to undesirable effects like warpage of the component.
- The annealing is carried out just below A_1 , wherein 'recovery*' processes are active (Annihilation of dislocations, polygonization).

Residual stresses → Heat below A_1 → Recovery

Annihilation of dislocations, polygonization

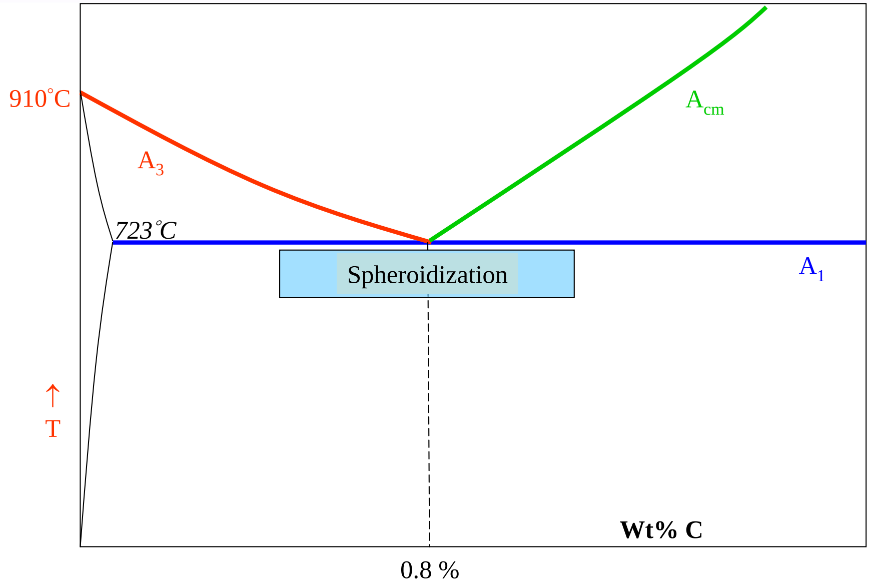
- Differential cooling
- Machining and cold working
- Martensite formation
- Welding



* *It is to be noted that 'recovery' is a technical term.*

Spheroidization Annealing

- This is a very specific heat treatment given to high carbon steel requiring extensive machining prior to final hardening & tempering. The main purpose of the treatment is to increase the ductility of the sample.
- Like stress relief annealing the treatment is done just below A_1.
- Long time heating leads cementite plates to form cementite spheroids. The driving force for this (microstructural) transformation is the reduction in interfacial energy.

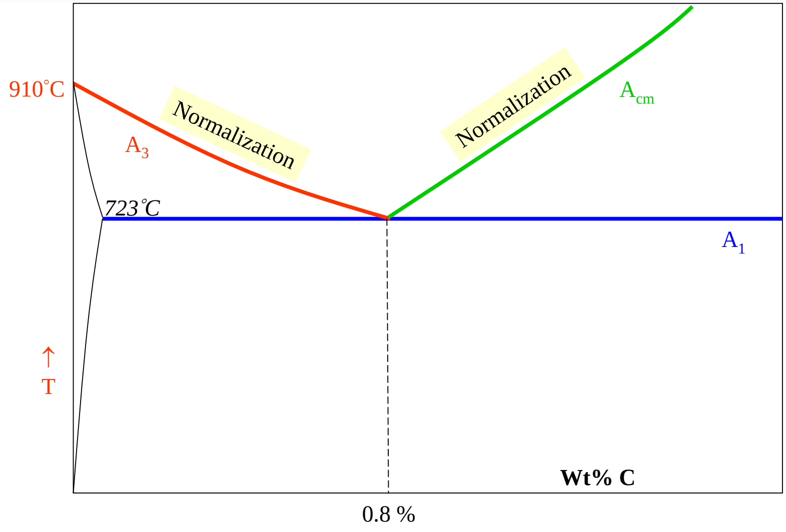


NORMALIZING

- The sample is heat above A_3 | A_{cm} to complete Austenization. The sample is then air cooled to obtain Fine pearlite. Fine pearlite has a reasonably good hardness and ductility.
- In hypo-eutectoid steels normalizing is done 50°C above the annealing temperature.
- In hyper-eutectoid steels normalizing done above A_{cm} → due to faster cooling cementite does not form a continuous film along GB.
- The list of uses of normalizing are listed below.

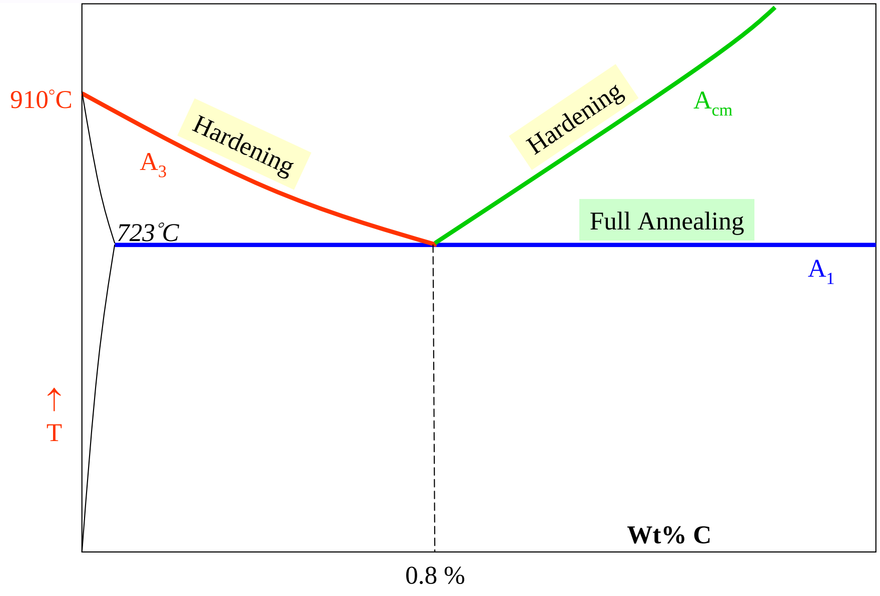
Purposes

- Refine grain structure prior to hardening
- To harden the steel slightly
- To reduce segregation in casting or forgings



HARDENING

- The sample is heated above A_3 | A_{cm} to cause Austenization. The sample is then quenched at a cooling rate higher than the critical cooling rate (i.e. to avoid the nose of the CCT diagram).
- The quenching process produces residual strains (thermal, phase transformation).
- The transformation to Martensite is usually not complete and the sample will have some retained Austenite.
- The Martensite produced is hard and brittle and tempering operation usually follows hardening. This gives a good combination of strength and toughness.



Severity of quench values of some typical quenching conditions

- Before we proceed further we note that we have a variety of quenching media at our disposal, with varying degrees of cooling effect. The severity of quench is indicated by the 'H' factor (defined below), with an ideal quench having a H-value of ∞.

Severity of Quench as indicated by the heat transfer equivalent H

$$H = \frac{f}{K} \qquad [m^{-1}]$$

f → heat transfer factor
K → Thermal conductivity

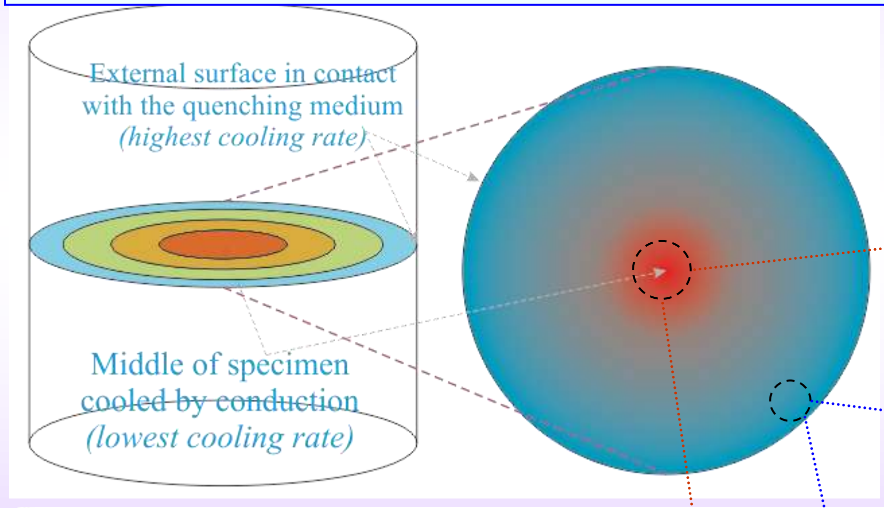
Process	Variable	H
Air	No agitation	0.02
Oil quench	No agitation	0.2
"	Slight agitation	0.35
"	Good agitation	0.5
"	Vigorous agitation	0.7
Water quench	No agitation	1.0
"	Vigorous agitation	1.5
Brine quench (saturated Salt water)	No agitation	2.0
"	Vigorous agitation	5.0
Ideal quench		∞

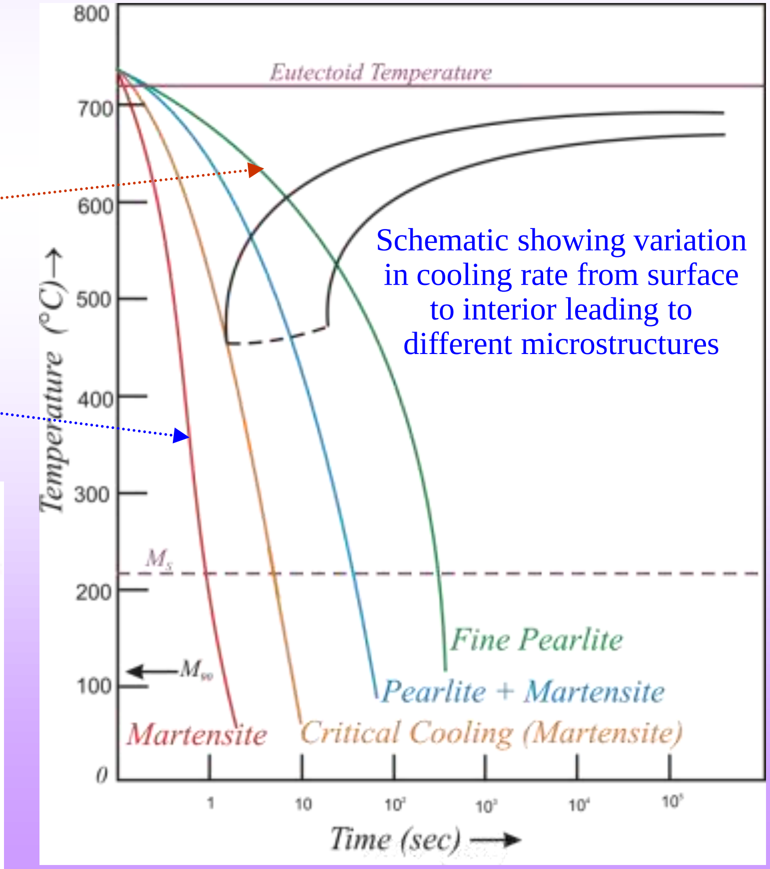
Increasing severity of quench

Note that apart from the nature of the quenching medium, the vigorousness of the shake determines the severity of the quench. When a hot solid is put into a liquid medium, gas bubbles form on the surface of the solid (interface with medium). As gas has a poor conductivity the quenching rate is reduced. Providing agitation (shaking the solid in the liquid) helps in bringing the liquid medium in direct contact with the solid; thus improving the heat transfer (and the cooling rate). The H value/index compares the relative ability of various media (gases and liquids) to cool a hot solid. Ideal quench is a conceptual idea with a heat transfer factor of ∞ (⇒ H = ∞).

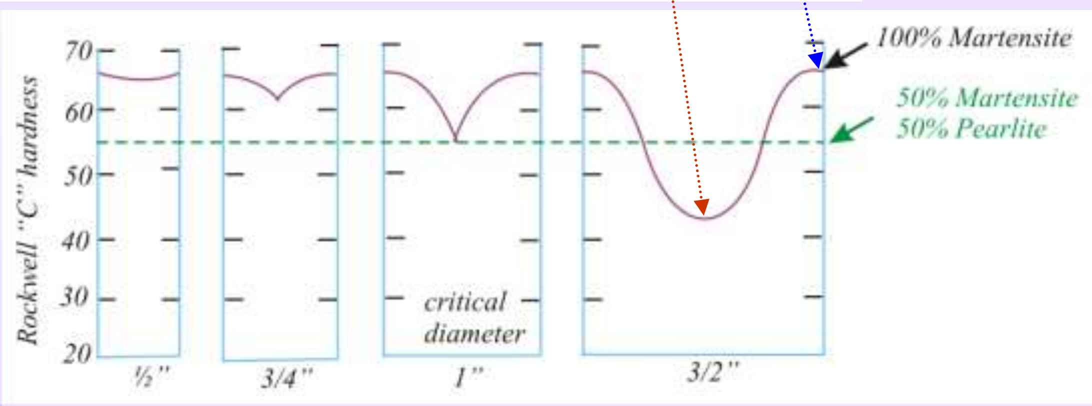
Through hardening of the sample

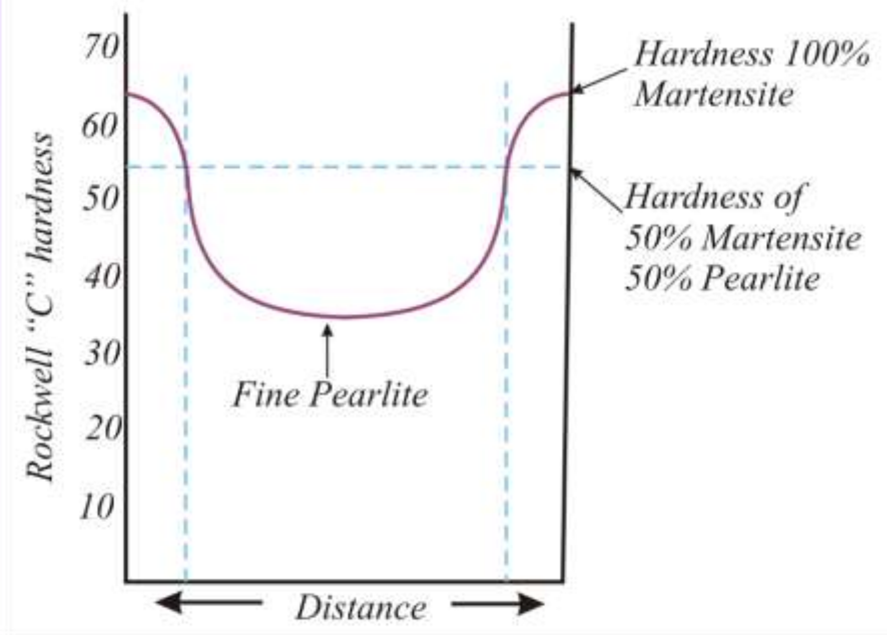
- ❑ The surface of is affected by the quenching medium and experiences the best possible cooling rate. The interior of the sample is cooled by conduction through the (hot) sample and hence experiences a lower cooling rate. This implies that different parts of the same sample follow different cooling curves on a CCT diagram and give rise to different microstructures.
- ❑ This gives to a varying hardness from centre to circumference. Critical diameter (d_c) is that diameter, which can be through hardened (i.e. we obtain 50% Martensite and 50% pearlite at the centre of the sample).





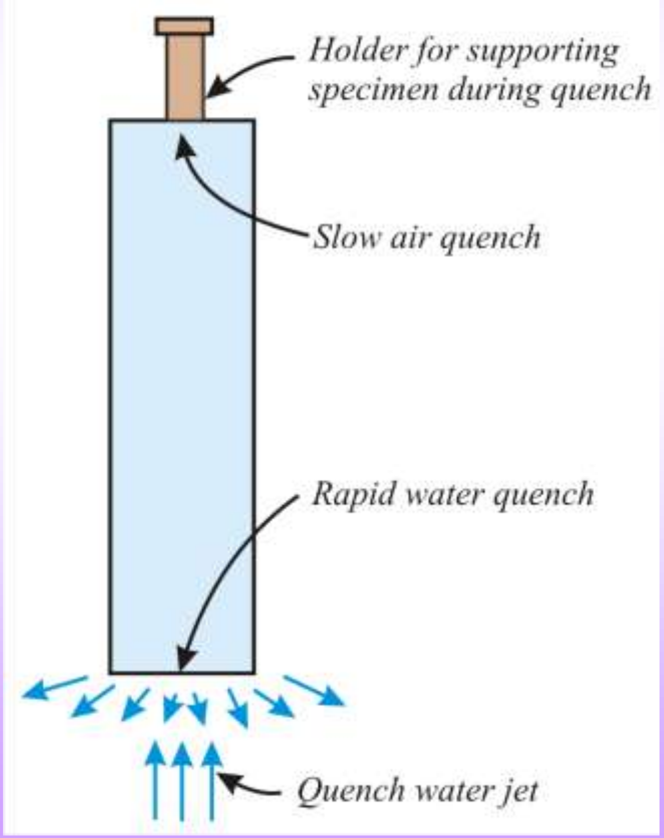
Schematic showing variation in cooling rate from surface to interior leading to different microstructures

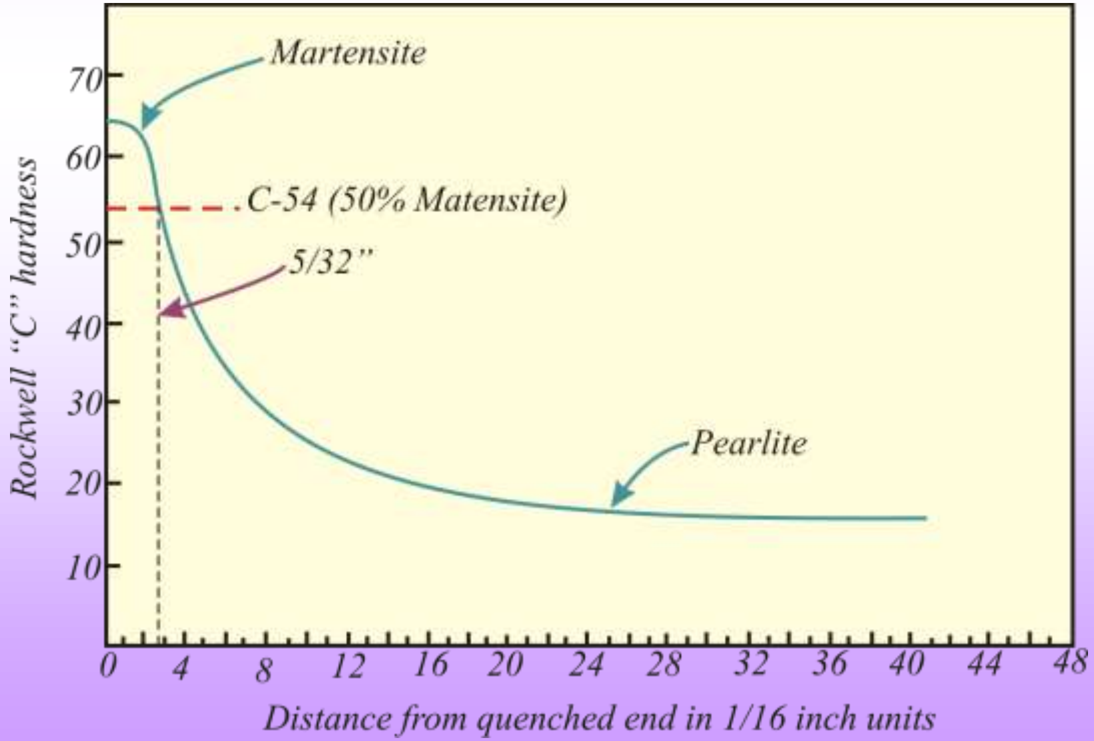




Typical hardness test survey made along a diameter of a quenched cylinder

Schematic of Jominy End Quench Test





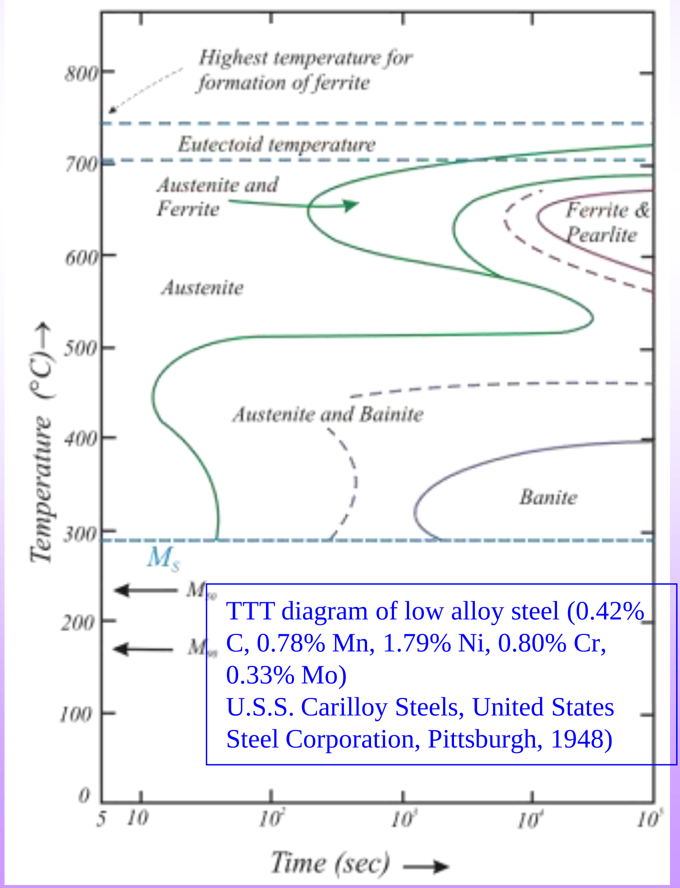
3. Grossman, M. A.. *Elements of Hardenability*, ASM, Cleveland, 1952.

Q & A

How to increase hardenability?

- Hardenability should not be confused with the ability to obtain high hardness. A material with low hardenability may have a higher surface hardness compared to another sample with higher hardenability.
- A material with a high hardenability can be cooled relatively slowly to produce 50% martensite (& 50% pearlite). A material with a high hardenability has the 'nose' of the CCT curve 'far' to the right (i.e. at higher times). Such a material can be through hardened easily.

- Hardenability of plain carbon steel can increased by alloying with most elements (it is to be noted that this is an added advantage as alloying is usually done to improve other properties).
- However, alloying gives two separate 'C-curves' for Pearlitic and Bainitic transformations (e.g. figure to the right).
- This implies that the 'nose' of the Bainitic transformation has to be avoided to get complete Martensite on quenching.



TTT diagram of low alloy steel (0.42% C, 0.78% Mn, 1.79% Ni, 0.80% Cr, 0.33% Mo)
U.S.S. Carilloy Steels, United States Steel Corporation, Pittsburgh, 1948)

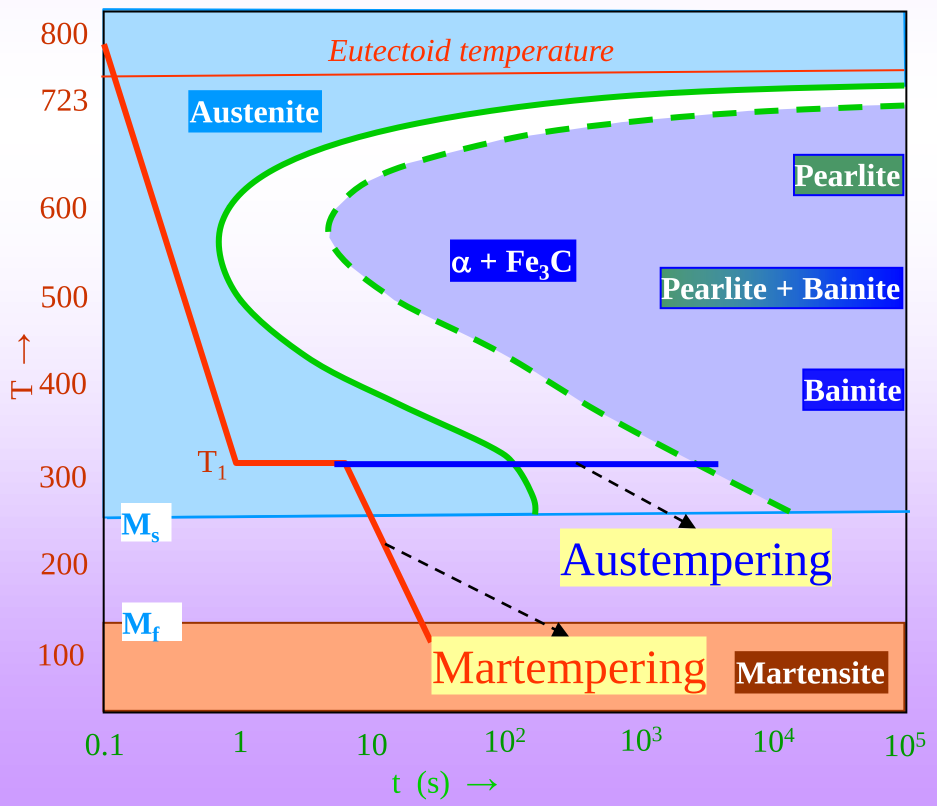
Tempering

$$\underset{Martensite}{\alpha'(BCT)} \xrightarrow{Temper} \underset{Ferrite}{\alpha\,(BCC)} + \underset{Cementite}{Fe_3C\,(OR)}$$

- ☐ A sample with martensitic microstructure is hard but brittle. Hence after quenching the sample (or component) is tempered. Maternsite being a metastable phase decomposes to ferrite and cementite on heating (providing thermal activation).
- ☐ Tempering is carried out just below the eutectoid temperature (heat → wait→ slow cool).
- ☐ In reality the microstructural changes which take place during tempering are very complex.
- ☐ The time temperature cycle for tempering is chosen so as to optimize strength and toughness. E.g. tool steel has a as quenched hardness of R_c65, which is tempered to get a hardness of R_c45-55.

MARTEMPERING & AUSTEMPERING

- These processes have been developed to avoid residual stresses generated during quenching.
- In both these processes Austenized steel is quenched above M_s (say to a temperature T_1) for homogenization of temperature across the sample.
- In Martempering the steel is then quenched and the entire sample transforms simultaneously to martensite. This is followed by tempering.
- In Austempering instead of quenching the sample, it is held at T_1 for it to transform to bainite.



Funda Check

Why do we need high hardenability?

Jominy End Quench Test

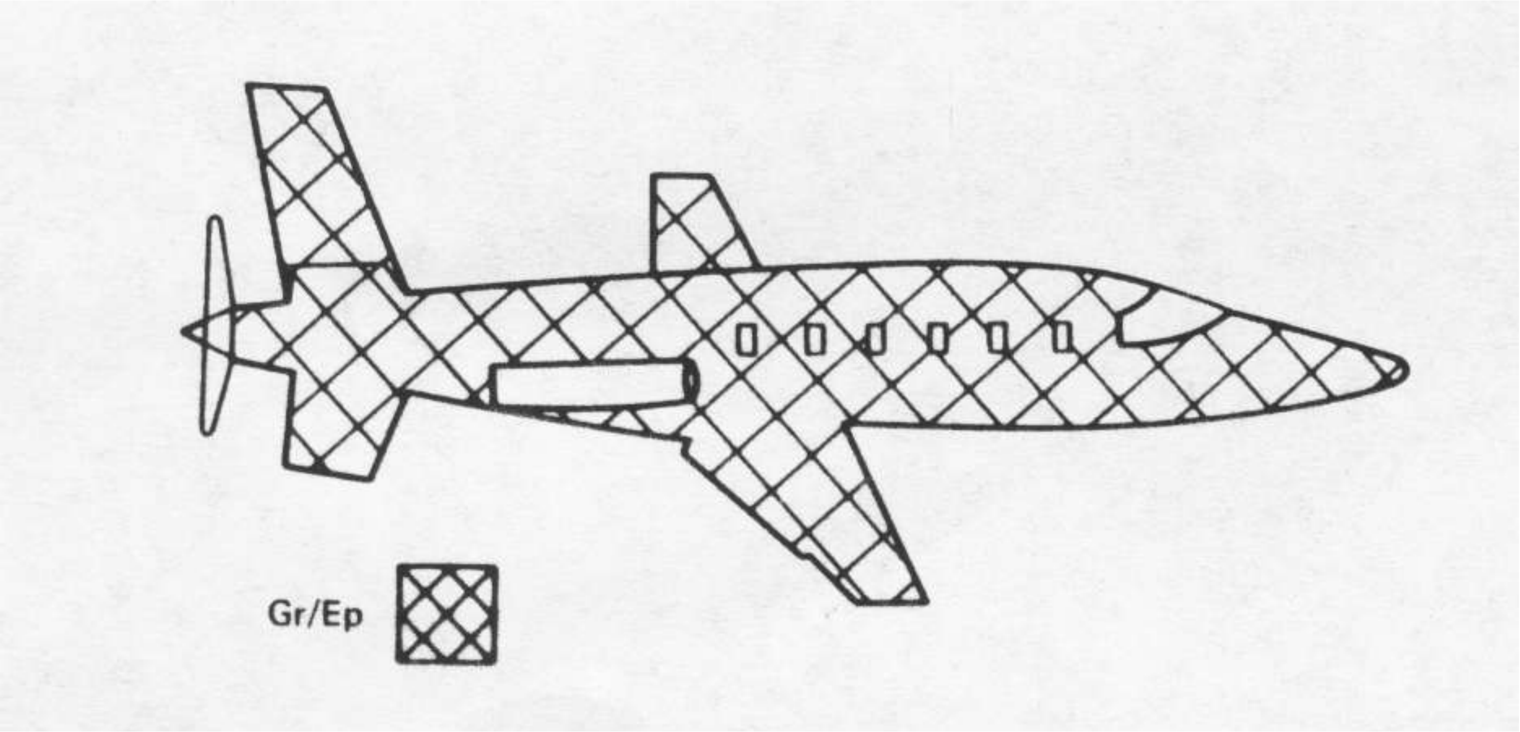
Composite Materials

Introduction

- A Composite material is a material system composed of two or more **macro constituents** that differ in shape and chemical composition and which are insoluble in each other. The history of composite materials dates back to early 20th century. In 1940, fiber glass was first used to reinforce epoxy.
- Applications:
  - Aerospace industry
  - Sporting Goods Industry
  - Automotive Industry
  - Home Appliance Industry

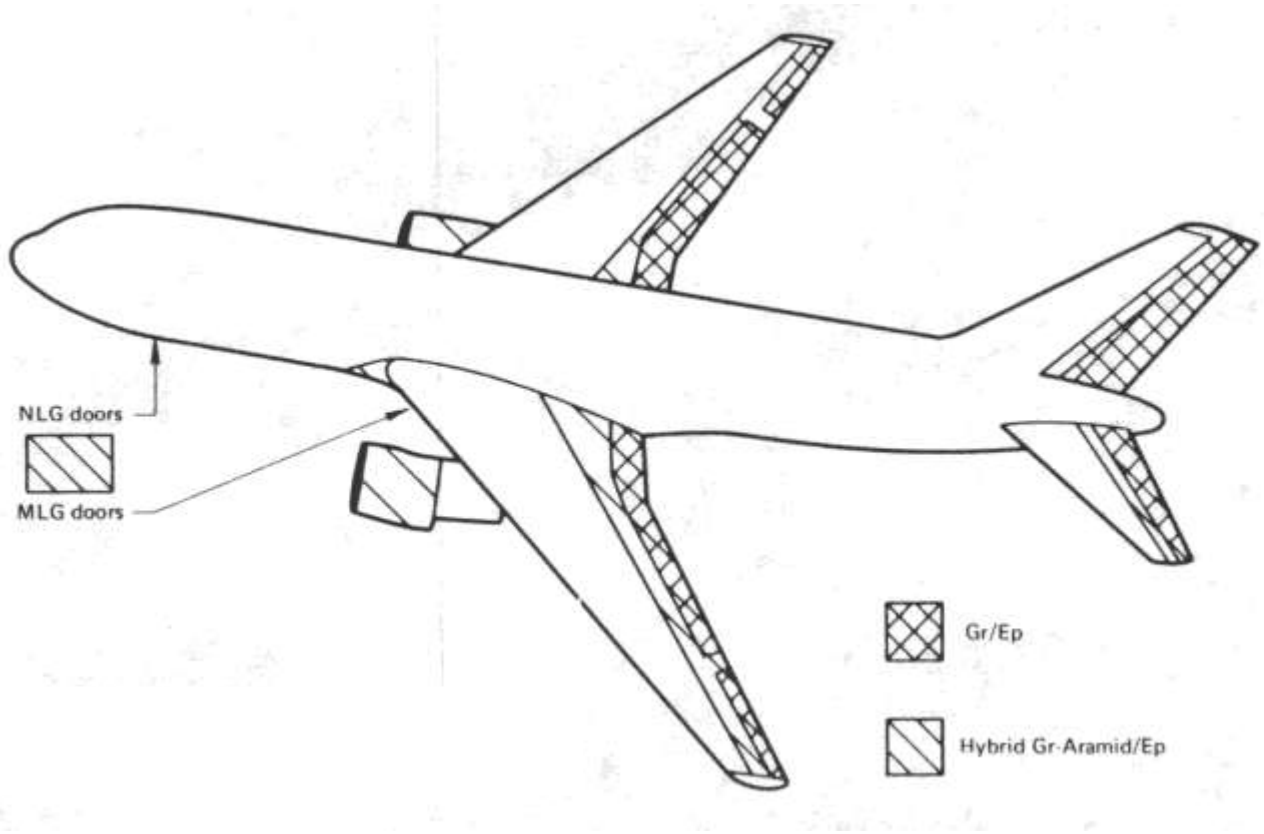
Advanced Aerospace Application:

Lear Fan 2100 “all-composite” aircraft



Advanced Aerospace Application:

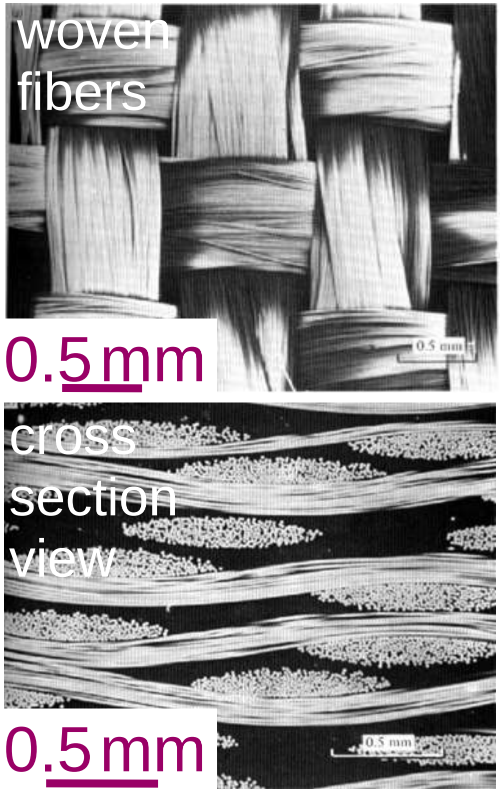
Boeing 767 (and in 777, 787 airplanes w/ the latest, full wing box is composite):



Terminology/Classification

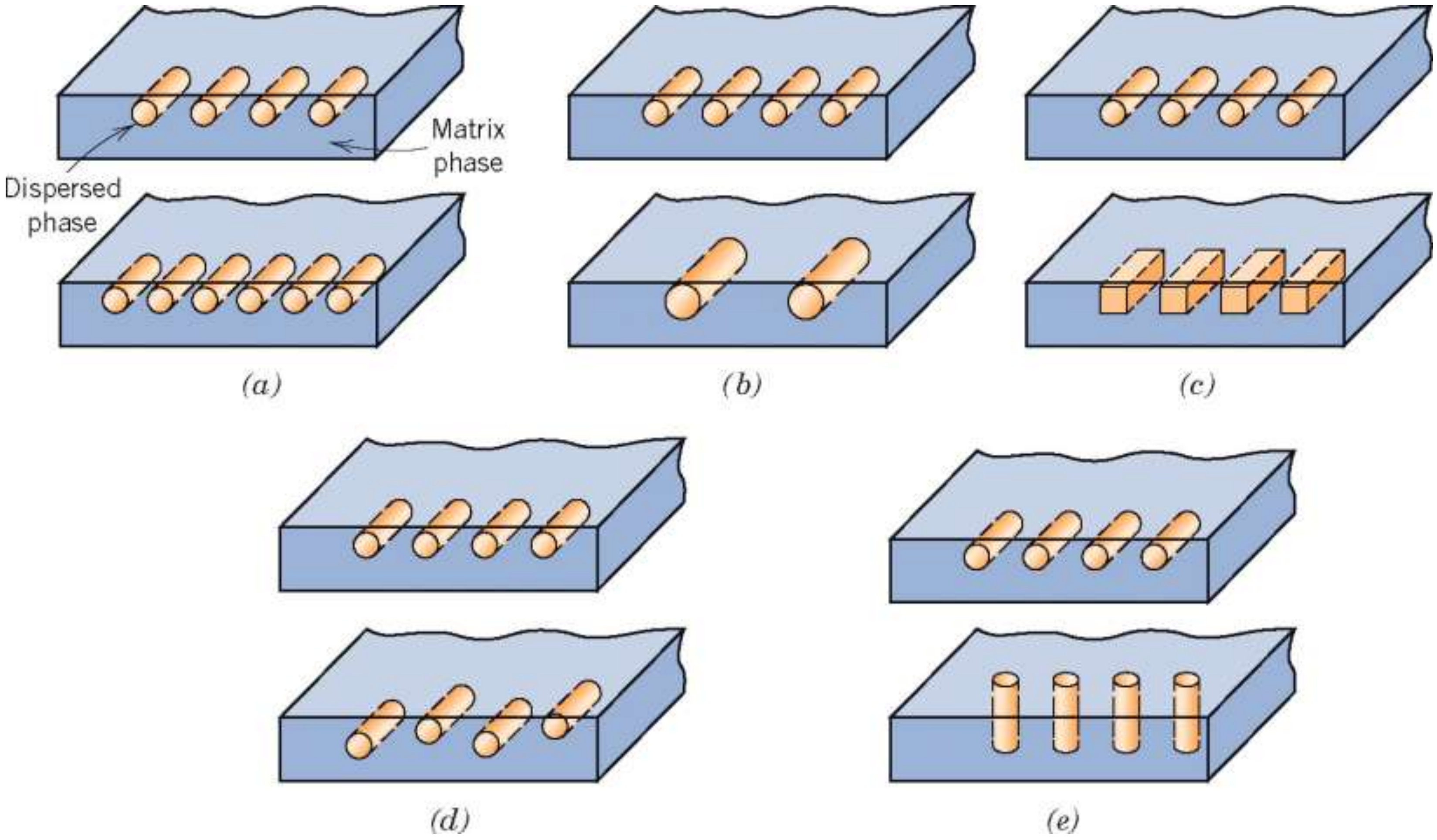
- Composites:
  - -- Multiphase material w/significant proportions of each phase.
- Matrix:
  - -- The continuous phase
  - -- Purpose is to:
    - - transfer stress to other phases
    - - protect phases from environment
  - -- Classification: MMC, CMC, PMC

    metal ceramic polymer
- Dispersed phase:
  - -- Purpose: enhance matrix properties.
    - MMC: increase σy, *TS*, creep resist.
    - CMC: increase K_c
    - PMC: increase *E*, σy, *TS*, creep resist.
  - -- Classification: Particle, fiber, structural

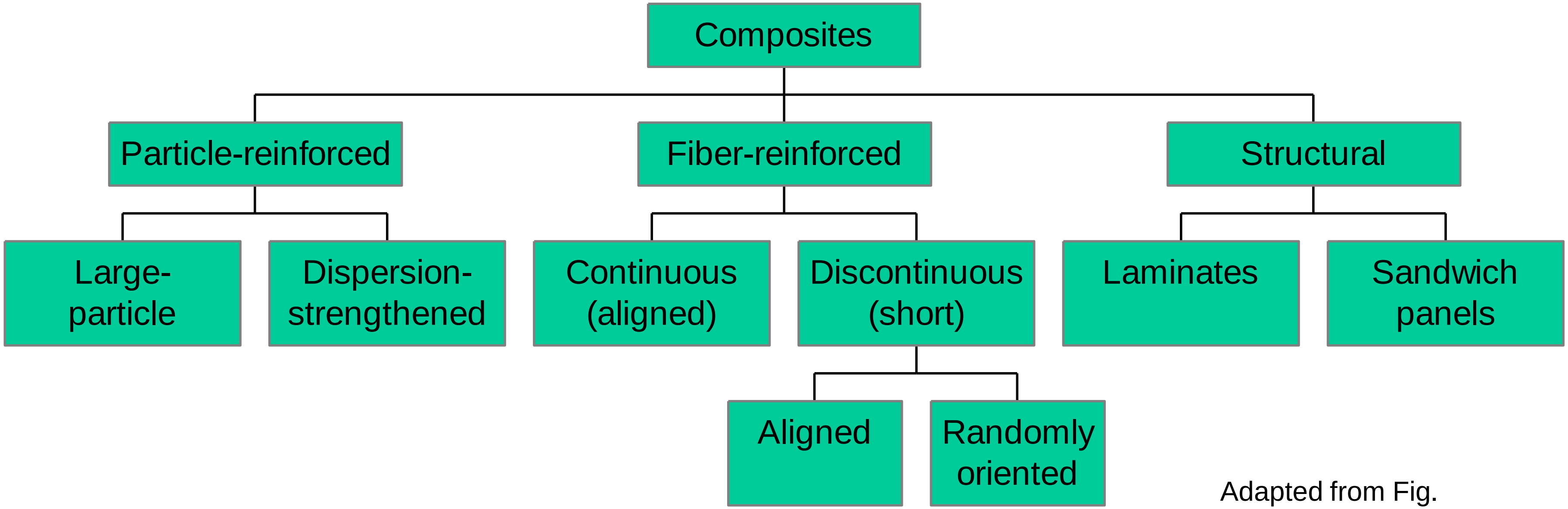


Reprinted with permission from D. Hull and T.W. Clyne, *An Introduction to Composite Materials*, 2nd ed., Cambridge University Press, New York, 1996, Fig. 3.6, p. 47.

Composite Structural Organization: the design variations



Composite Survey


Composites

Particle-reinforced

Fiber-reinforced

Structural

Large-particle

Dispersion-strengthened

Continuous (aligned)

Discontinuous (short)

Laminates

Sandwich panels

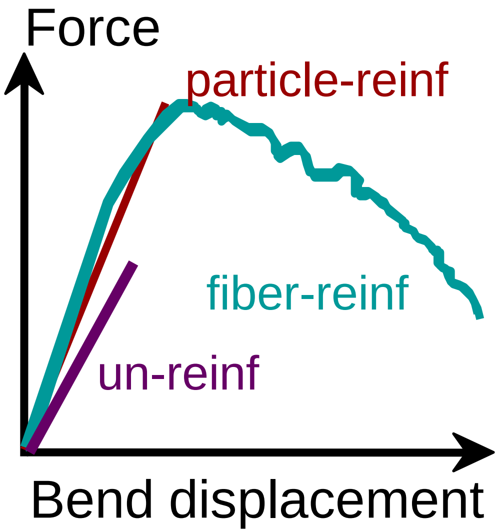
Aligned

Randomly oriented

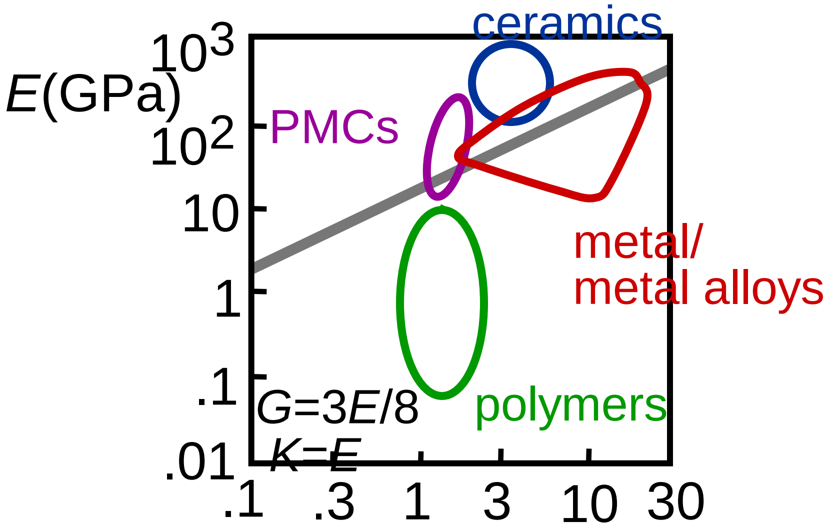
Adapted from Fig. 16.2, *Callister 7e*.

Composite Benefits

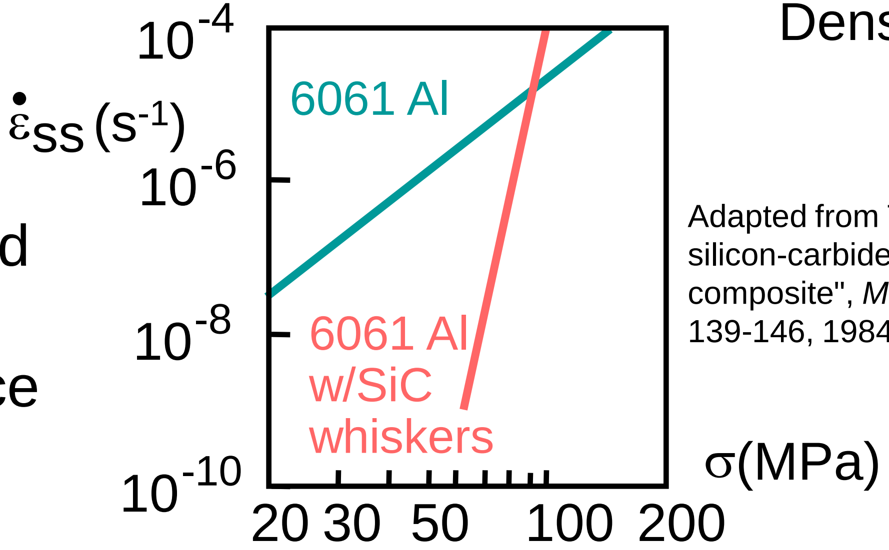
- CMCs: Increased toughness



- PMCs: Increased E/ρ



- MMCs:
  Increased creep resistance



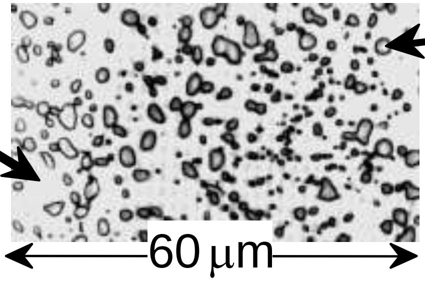
Adapted from T.G. Nieh, "Creep rupture of a silicon-carbide reinforced aluminum composite", *Metall. Trans. A* Vol. 15(1), pp. 139-146, 1984. Used with permission.

Composite Survey: Particle-I

Particle-reinforced | Fiber-reinforced | Structural

- Examples:
  - Spheroidite steel

matrix: ferrite (α) (ductile)

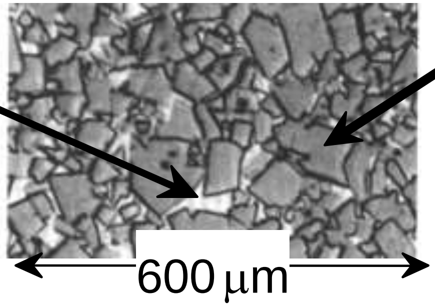


particles: cementite (Fe_3C) (brittle)

Adapted from Fig. 10.19, *Callister 7e*. (Fig. 10.19 is copyright United States Steel Corporation, 1971.)

  - WC/Co cemented carbide

matrix: cobalt (ductile)
V_m: 5-12 vol%!

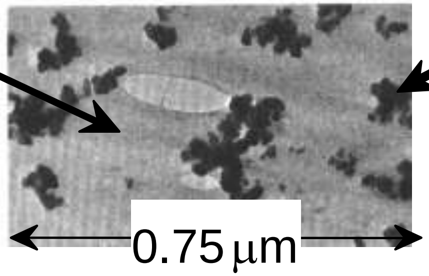


particles: WC (brittle, hard)

Adapted from Fig. 16.4, *Callister 7e*. (Fig. 16.4 is courtesy Carboloy Systems, Department, General Electric Company.)

  - Automobile tires

matrix: rubber (compliant)



particles: C (stiffer)

Adapted from Fig. 16.5, *Callister 7e*. (Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)

Composite Survey: Particle-II

Particle-reinforced Fiber-reinforced Structural

Concrete – gravel + sand + cement

- Why sand *and* gravel? Sand packs into gravel voids

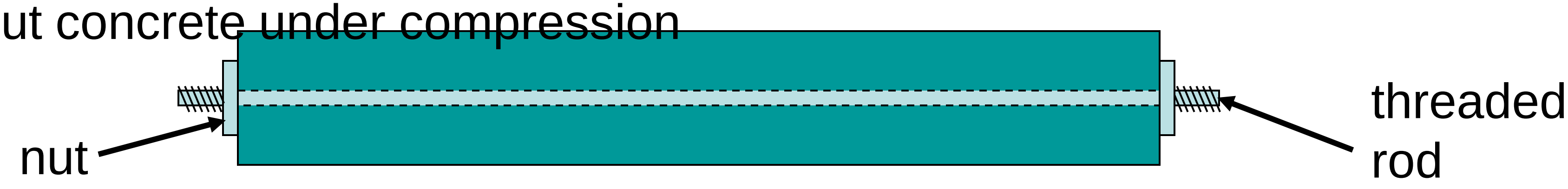
Reinforced concrete - Reinforce with steel rebar or remesh

- increases strength - even if cement matrix is cracked

Prestressed concrete - remesh under tension during setting of concrete. Tension release puts concrete under compressive force

- Concrete much stronger under compression.
- Applied tension must exceed compressive force

Post tensioning – tighten nuts to put under rod under tension but concrete under compression



Composite Survey: Particle-III

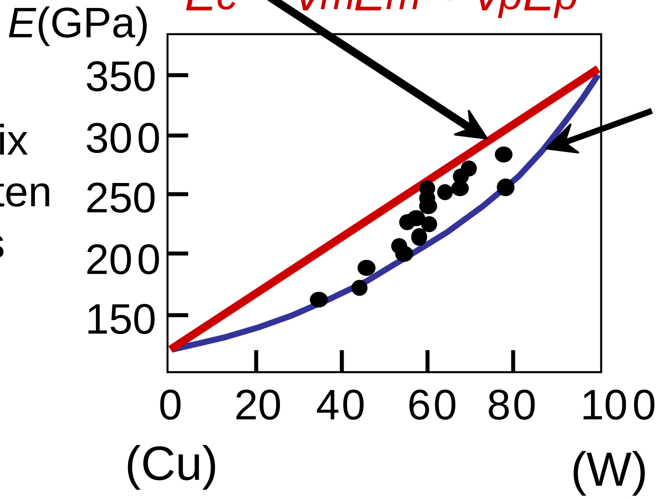
Particle-reinforced Fiber-reinforced Structural

- Elastic modulus, E_c, of composites:
  -- two approaches.

upper limit: "rule of mixtures"

$$E_c = V_m E_m + V_p E_p$$

Data:
Cu matrix
w/tungsten
particles



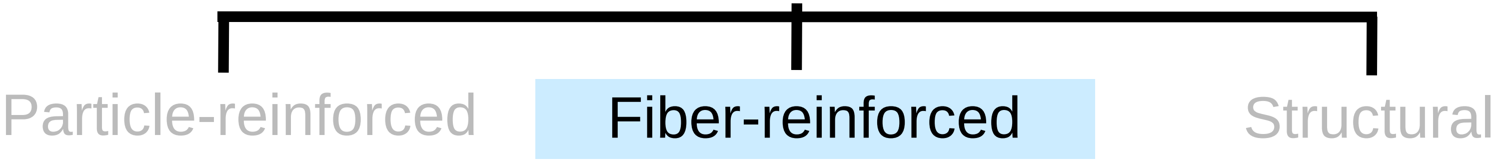
lower limit:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$

Adapted from Fig. 16.3, *Callister 7e*. (Fig. 16.3 is from R.H. Krock, *ASTM Proc*, Vol. 63, 1963.)

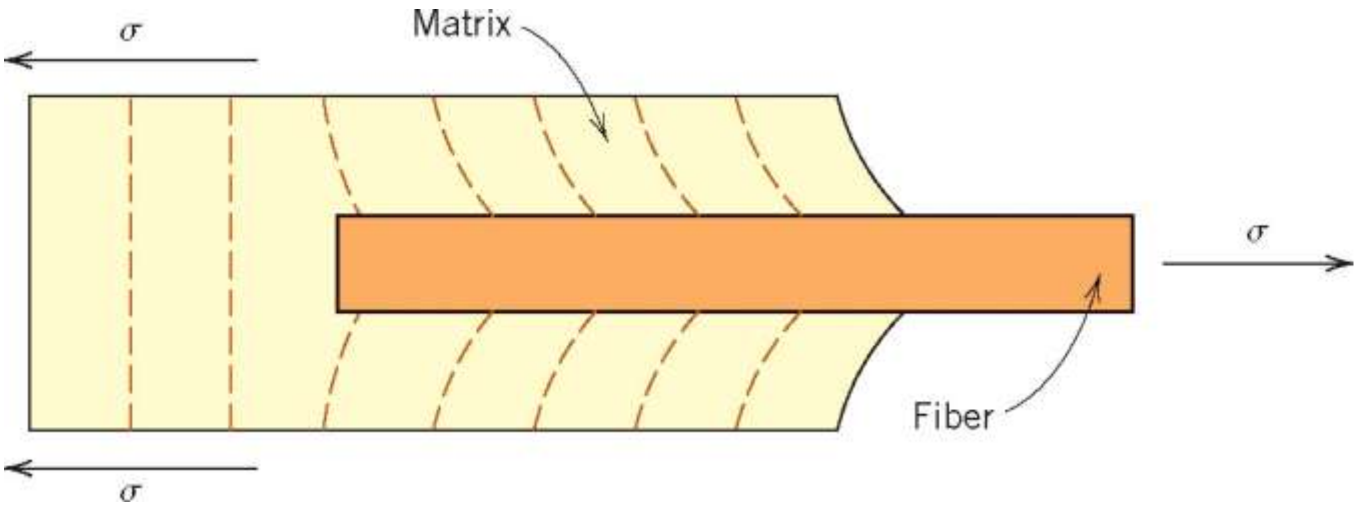
- Application to other properties:
  -- Electrical conductivity, σ_e: Replace E in the above equations with σ_e.
  -- Thermal conductivity, k: Replace E in above equations with k.

Composite Survey: Fiber


Particle-reinforced
Fiber-reinforced
Structural

- Fibers themselves are very strong
  - – Provide significant strength improvement to material
  - – **Ex: fiber-glass**
    - **Continuous glass filaments in a polymer matrix**
    - **Strength due to fibers**
    - **Polymer simply holds them in place and environmentally protects them**

Fiber Loading Effect under Stress:



Composite Survey: Fiber

Particle-reinforced

Fiber-reinforced

Structural

- Critical fiber length (l_C) for effective stiffening & strengthening:

fiber strength in tension

fiber diameter

$$\text{fiber length} > 15\frac{\sigma_f d}{\tau_c}$$

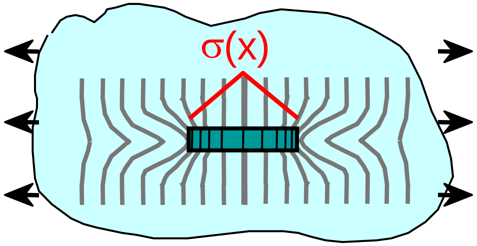
shear strength of **fiber-matrix** interface

- Ex: For fiberglass, a fiber length > 15 mm is needed since this length provides a “Continuous fiber” based on usual glass fiber properties

- Why? Longer fibers carry stress more efficiently!

Shorter, thicker fiber:

$$\text{fiber length} < 15\frac{\sigma_f d}{\tau_c}$$

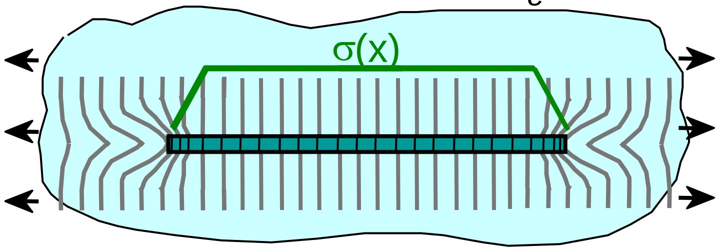


Poorer fiber efficiency

Adapted from Fig. 16.7, *Callister 7e*.

Longer, thinner fiber:

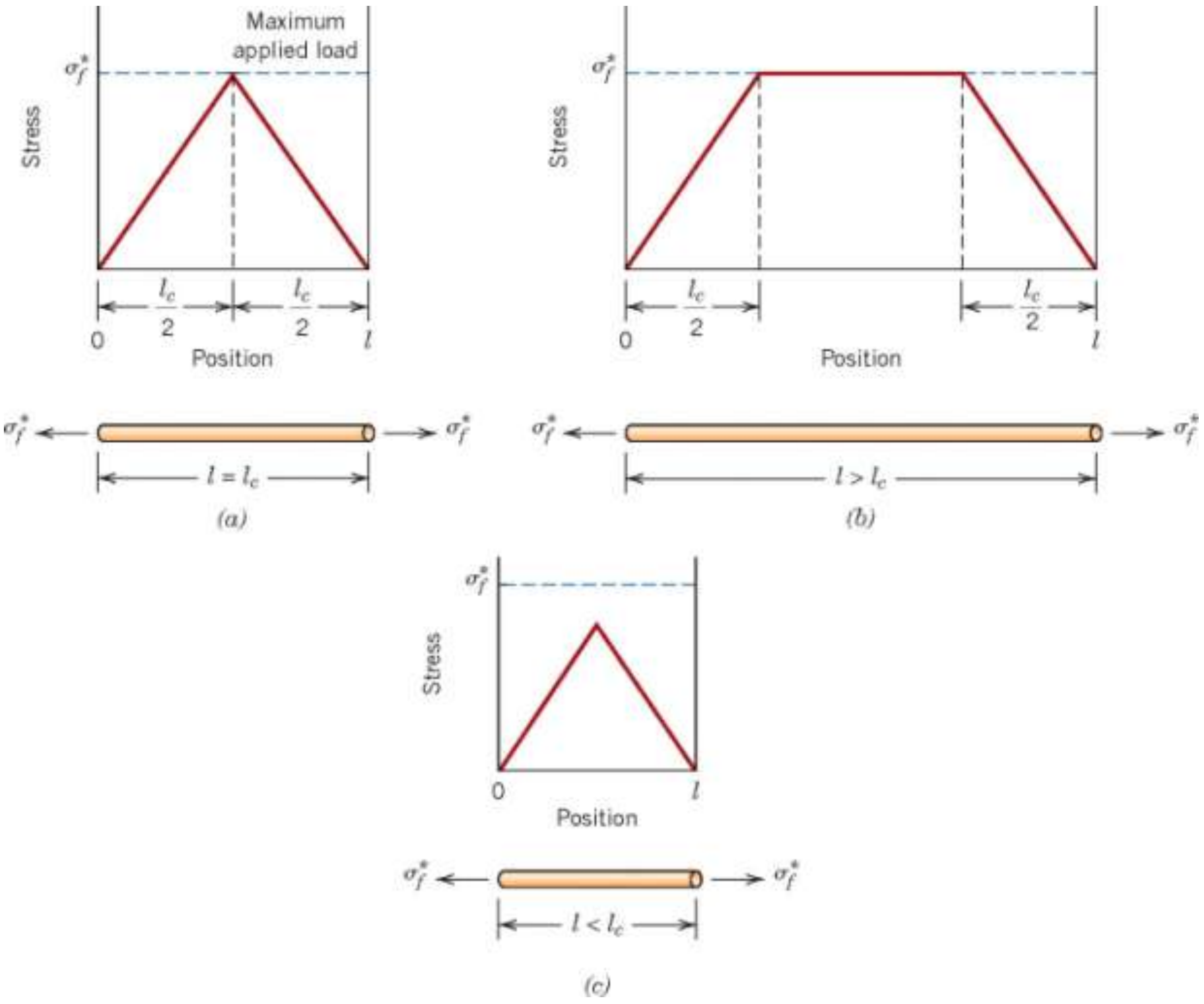
$$\text{fiber length} > 15\frac{\sigma_f d}{\tau_c}$$



Better fiber efficiency

Fiber Load Behavior under Stress:

$$l_c = \frac{\sigma^*{}_f d}{2\tau_c}$$

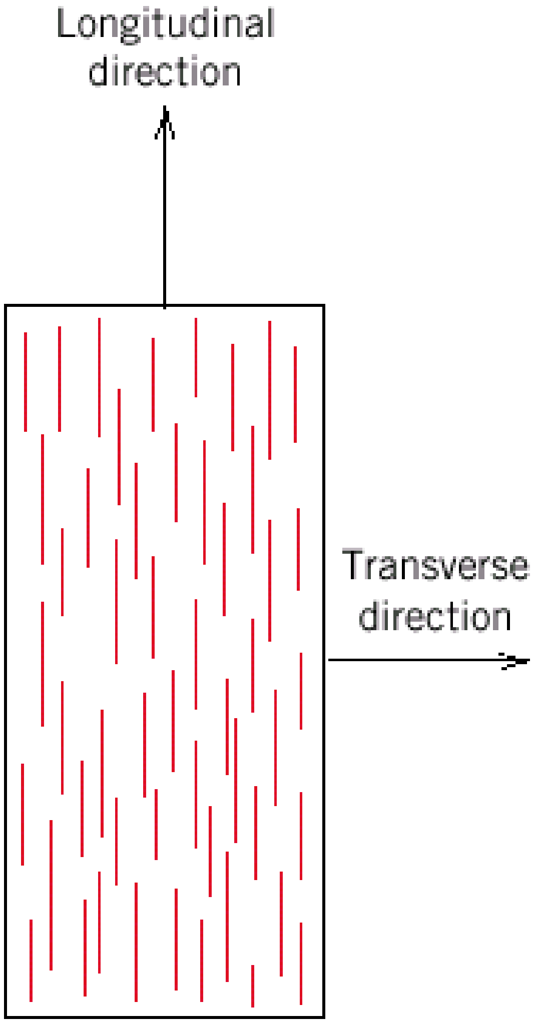


Composite Survey: Fiber

Particle-reinforced | **Fiber-reinforced** | Structural

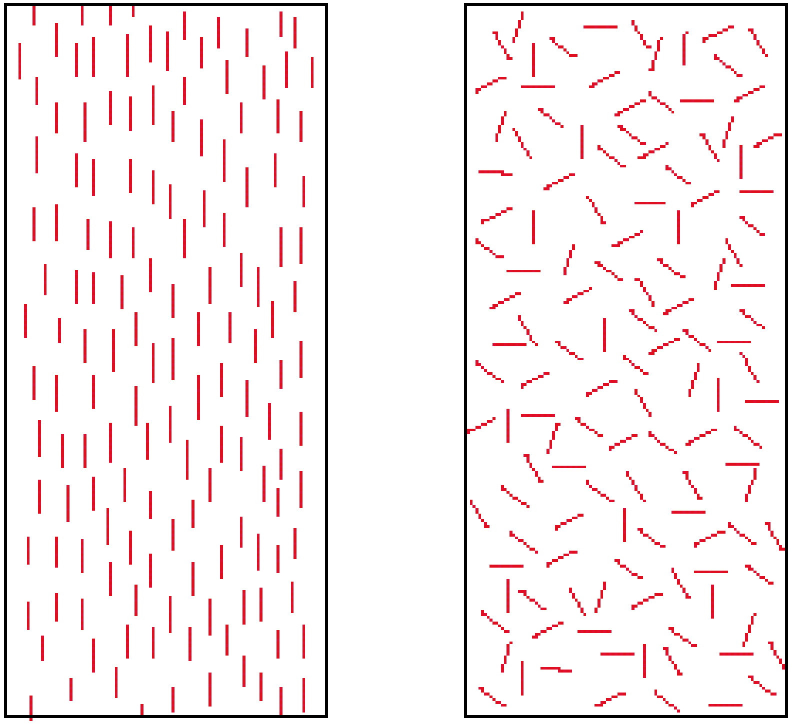
- Fiber Materials
  - Whiskers - Thin single crystals - large length to diameter ratio
    - graphite, SiN, SiC
    - high crystal perfection – extremely strong, strongest known
    - very expensive
  - Fibers
    - polycrystalline or amorphous
    - generally polymers or ceramics
    - Ex: Al_2O_3 , Aramid, E-glass, Boron, UHMWPE
  - Wires
    - Metal – steel, Mo, W

Fiber Alignment



aligned
continuous

Adapted from Fig. 16.8, *Callister 7e*.

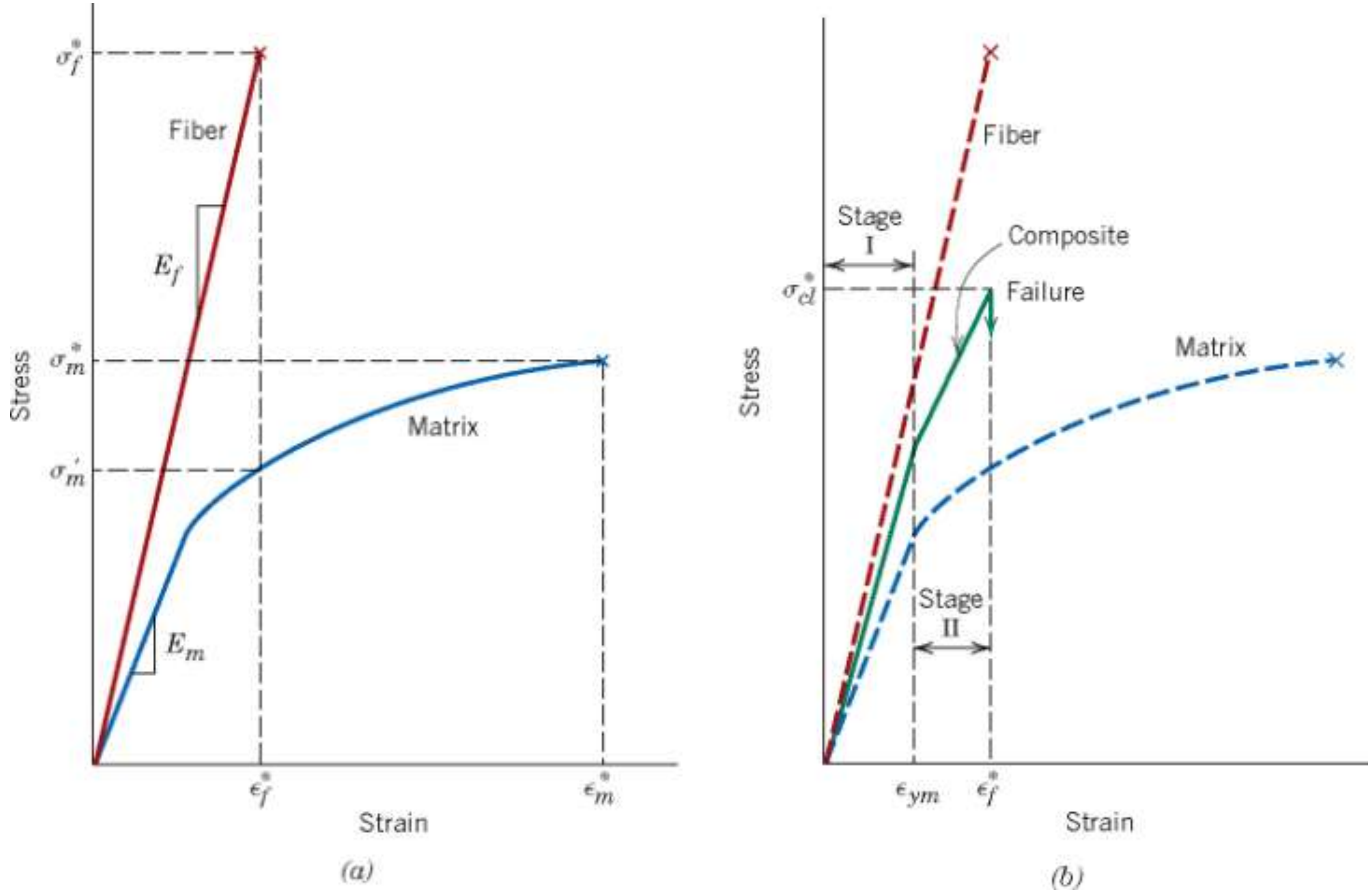


aligned

random

discontinuous

Behavior under load for Fibers & Matrix



Composite Strength: Longitudinal Loading

Continuous fibers - Estimate fiber-reinforced composite strength for long continuous fibers in a matrix

- Longitudinal deformation

$$\sigma_c = \sigma_m \underset{\uparrow}{V_m} + \sigma_f \underset{\uparrow}{V_f} \qquad \text{but} \qquad \varepsilon_c \underset{\uparrow}{=} \varepsilon_m = \varepsilon_f$$

volume fraction

isostrain

$$\therefore \qquad \boxed{E_{ce} = E_m V_m + E_f V_f}$$

longitudinal (extensional) modulus

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

f = fiber
m = matrix

Remembering: $E = \sigma/\varepsilon$ and note, this model corresponds to the "upper bound" for particulate composites

Composite Strength: Transverse Loading

- In transverse loading the fibers carry less of the load and are in a state of ‘isostress’

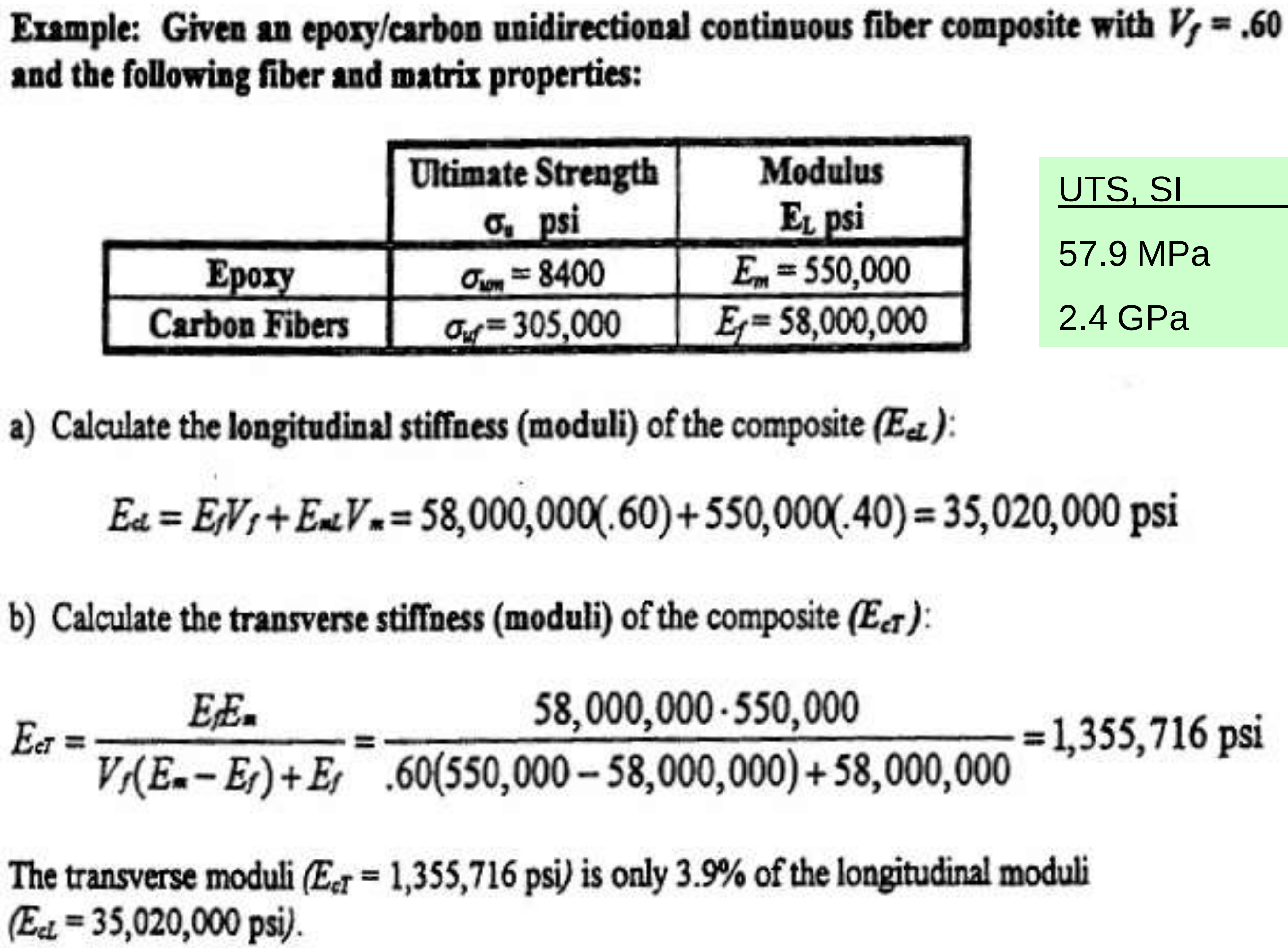
$$\sigma_c = \sigma_m = \sigma_f = \sigma \qquad \varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$$

$$\therefore \quad \boxed{\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}}$$

transverse modulus

Remembering: $E = \sigma/\varepsilon$ and note, this model corresponds to the “lower bound” for particulate composites

An Example:



Example: Given an epoxy/carbon unidirectional continuous fiber composite with $V_f = .60$ and the following fiber and matrix properties:

	Ultimate Strength σ_u psi	**Modulus E_L psi**
Epoxy	$\sigma_{um} = 8400$	$E_m = 550{,}000$
Carbon Fibers	$\sigma_{uf} = 305{,}000$	$E_f = 58{,}000{,}000$

UTS, SI	Modulus, SI
57.9 MPa	3.8 GPa
2.4 GPa	399.9 GPa

a) Calculate the **longitudinal stiffness (moduli)** of the composite (E_{cL}):

$$E_{cL} = E_f V_f + E_{mL} V_m = 58{,}000{,}000(.60) + 550{,}000(.40) = 35{,}020{,}000 \text{ psi}$$

(241.5 GPa)

b) Calculate the **transverse stiffness (moduli)** of the composite (E_{cT}):

$$E_{cT} = \frac{E_f E_m}{V_f(E_m - E_f) + E_f} = \frac{58{,}000{,}000 \cdot 550{,}000}{.60(550{,}000 - 58{,}000{,}000) + 58{,}000{,}000} = 1{,}355{,}716 \text{ psi}$$

(9.34 GPa)

The transverse moduli $(E_{cT} = 1{,}355{,}716$ psi$)$ is only 3.9% of the longitudinal moduli $(E_{cL} = 35{,}020{,}000$ psi$)$.

Note: (for ease of conversion)

6870 N/m^2 per psi!

Composite Strength

Particle-reinforced | Fiber-reinforced | Structural

- Estimate of E_c and TS for discontinuous fibers:

-- valid when fiber length $> 15\dfrac{\sigma_f d}{\tau_c}$

-- Elastic modulus in fiber direction:

$$E_c = E_m V_m + K E_f V_f$$

efficiency factor:

-- aligned 1D: $K = 1$ (aligned $\parallel$)
-- aligned 1D: $K = 0$ (aligned $\perp$)
-- random 2D: $K = 3/8$ (2D isotropy)
-- random 3D: $K = 1/5$ (3D isotropy)

Values from Table 16.3, *Callister 7e*. (Source for Table 16.3 is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

-- TS in fiber direction:

$$(TS)_c = (TS)_m V_m + (TS)_f V_f$$ (aligned 1D)

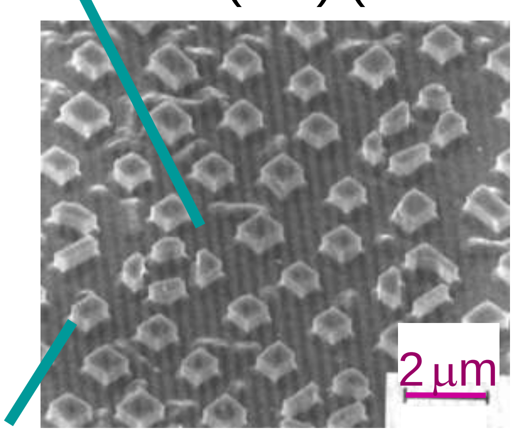
Composite Survey: Fiber

Particle-reinforced | **Fiber-reinforced** | Structural

- Aligned Continuous fibers
- Examples:

-- Metal: $\gamma'(Ni_3Al)$-$\alpha(Mo)$
by eutectic solidification.

matrix: α (Mo) (ductile)

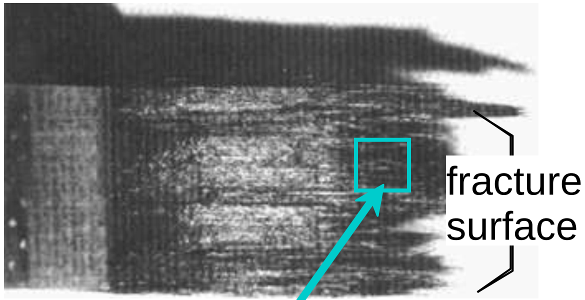


fibers: γ' (Ni_3Al) (brittle)

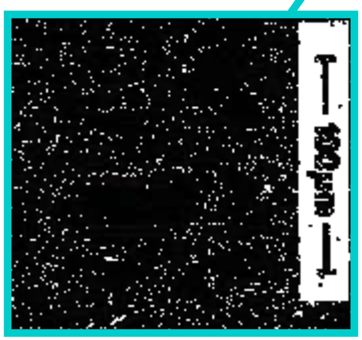
From W. Funk and E. Blank, “Creep deformation of Ni3Al-Mo in-situ composites", *Metall. Trans. A* Vol. 19(4), pp. 987-998, 1988. Used with permission.

-- Ceramic: Glass w/SiC fibers
formed by glass slurry
E_{glass} = 76 GPa; E_{SiC} = 400 GPa.

(a)

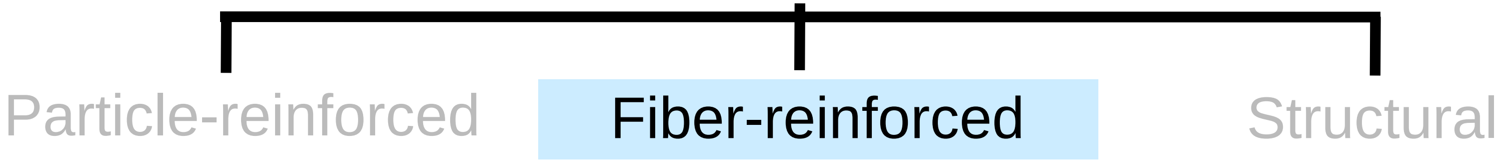


(b)



From F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.22, p. 145 (photo by J. Davies); (b) Fig. 11.20, p. 349 (micrograph by H.S. Kim, P.S. Rodgers, and R.D. Rawlings). Used with permission of CRC Press, Boca Raton, FL.

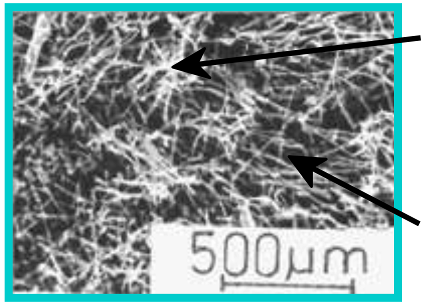
Composite Survey: Fiber



- Discontinuous, random 2D fibers
- Example: Carbon-Carbon
  - -- process: fiber/pitch, then burn out at up to 2500ºC.
  - -- uses: disk brakes, gas turbine exhaust flaps, nose cones.

- Other variations:
  - -- Discontinuous, random 3D
  - -- Discontinuous, 1D

(b)

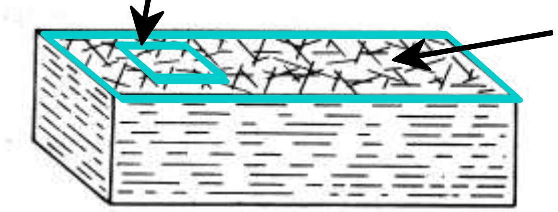


C fibers: very stiff very strong

C matrix: less stiff less strong

view onto plane

(a)



fibers lie in plane

$$E_c = E_m V_m + K E_f V_f$$

efficiency factor:

-- random 2D: $K = 3/8$ (2D isotropy)

-- random 3D: $K = 1/5$ (3D isotropy)

Looking at strength:

$$l > l_C$$

$$\sigma_{cd}^{*} = \sigma_f^{*} V_f \left(1 - {l_C}\big/{2l}\right) + \sigma_m^{'}\left(1 - V_f\right)$$

where σ_f^{*} is fiber fracture strength

& $\sigma_m^{'}$ is matrix stress when composite fails

$$l < l_C$$

$$\sigma_{cd'}^{*} = \frac{l\tau_C}{d} V_f + \sigma_m^{'}\left(1 - V_f\right)$$

where: d is fiber diameter &

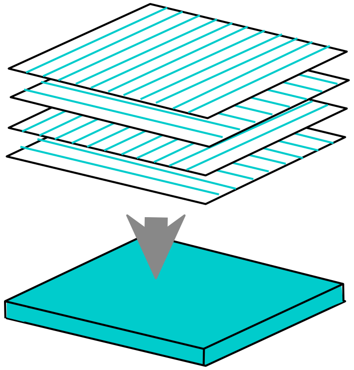
τ_C is smaller of Matrix Fiber shear strength

or matrix shear yield strength

Composite Survey: Structural

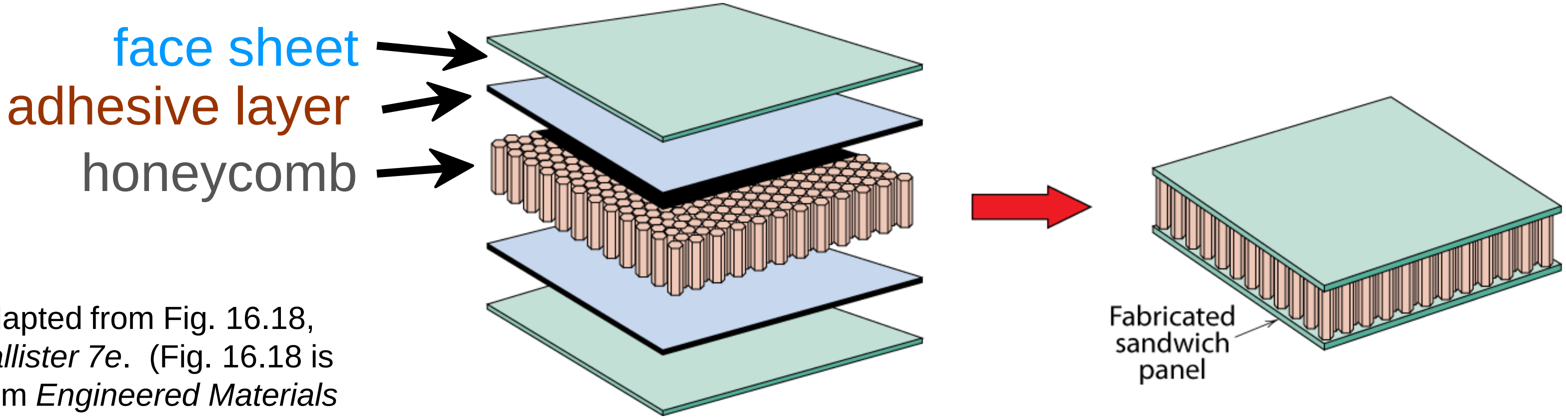
Particle-reinforced   Fiber-reinforced   **Structural**

- Stacked and bonded fiber-reinforced sheets
  - -- stacking sequence: e.g., 0º/90º or 0°/45°/90°
  - -- benefit: balanced, in-plane stiffness



Adapted from Fig. 16.16, *Callister 7e*.

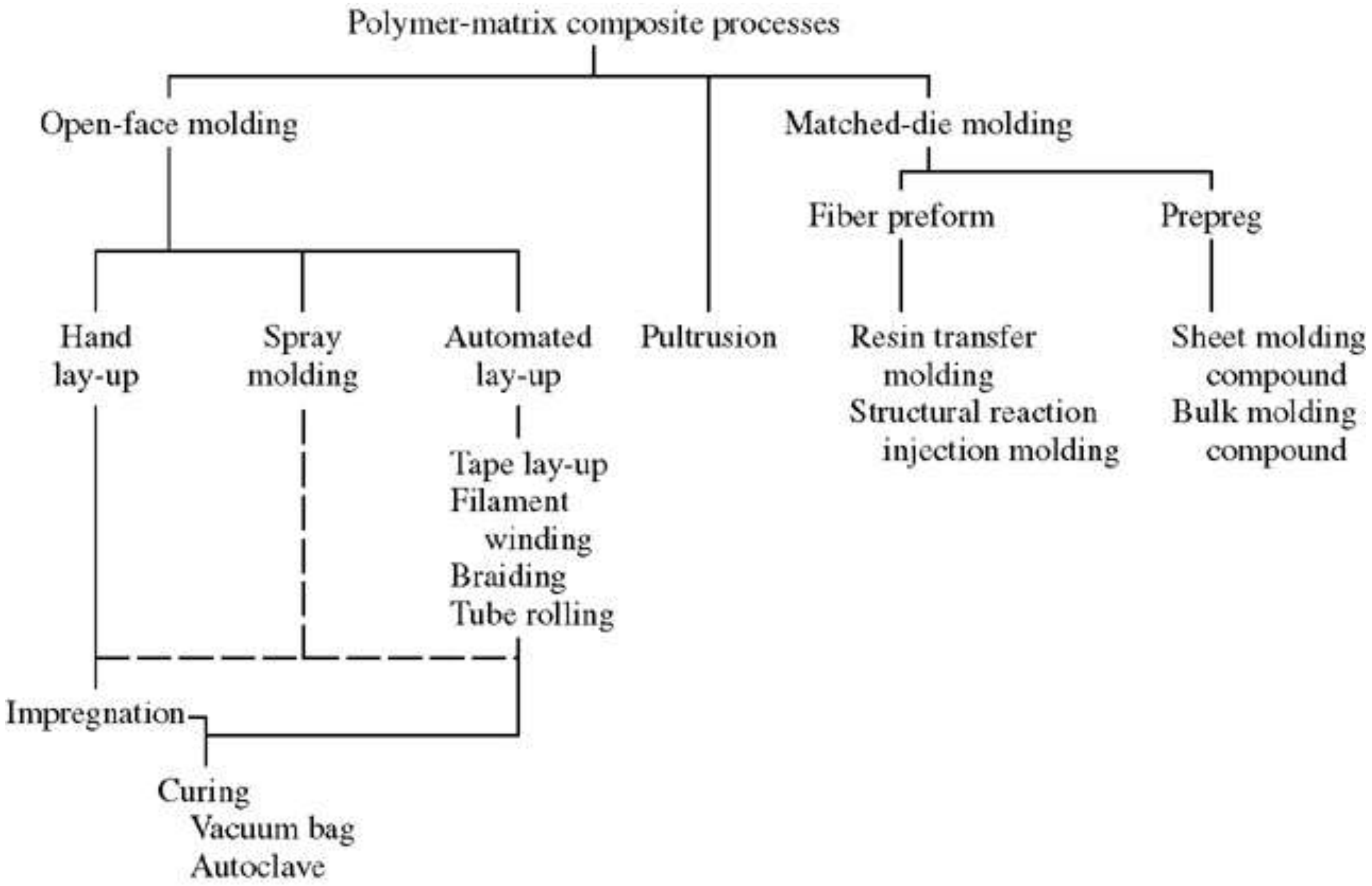
- Sandwich panels
  - -- low density, honeycomb core
  - -- benefit: light weight, large bending stiffness



Adapted from Fig. 16.18, *Callister 7e*. (Fig. 16.18 is from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Materials Park, OH, 1987.)

Composite Manufacturing Processes

- Particulate Methods: Sintering
- Fiber reinforced: Several
- Structural: Usually Hand lay-up and atmospheric curing or vacuum curing



Polymer-matrix composite processes

Open-face molding

Hand lay-up

Spray molding

Automated lay-up

Tape lay-up
Filament winding
Braiding
Tube rolling

Impregnation

Curing
Vacuum bag
Autoclave

Pultrusion

Matched-die molding

Fiber preform

Resin transfer molding
Structural reaction injection molding

Prepreg

Sheet molding compound
Bulk molding compound

figure 15.4

Open Mold Processes

Only one mold (male or female) is needed and may be made of any material such as wood, reinforced plastic or , for longer runs, sheet metal or electroformed nickel. The final part is usually very smooth.

Shaping. Steps that may be taken for high quality

1. Mold release agent (silicone, polyvinyl alcohol, fluorocarbon, or sometimes, plastic film) is first applied.
2. Unreinforced surface layer (gel coat) may be deposited for best surface quality.

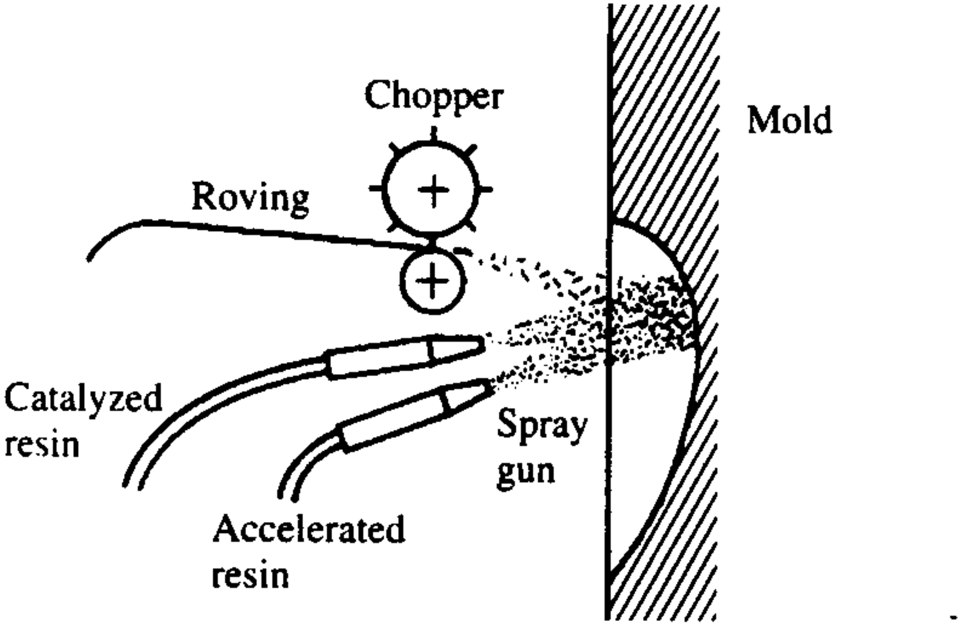
Hand Lay-Up: The resin and fiber (or pieces cut from prepreg) are placed manually, air is expelled with squeegees and if necessary, multiple layers are built up.

- Hardening is at room temperature but may be improved by heating.
- Void volume is typically 1%.
- Foam cores may be incorporated (and left in the part) for greater shape complexity. Thus essentially all shapes can be produced.
- Process is slow (deposition rate around 1 kg/h) and labor-intensive
- Quality is highly dependent on operator skill.
- Extensively used for products such as airframe components, boats, truck bodies, tanks, swimming pools, and ducts.

SPRAY-UP MOLDING

A spray gun supplying resin in two converging streams into which roving is chopped

- Automation with robots results in highly reproducible production
- Labor costs are lower

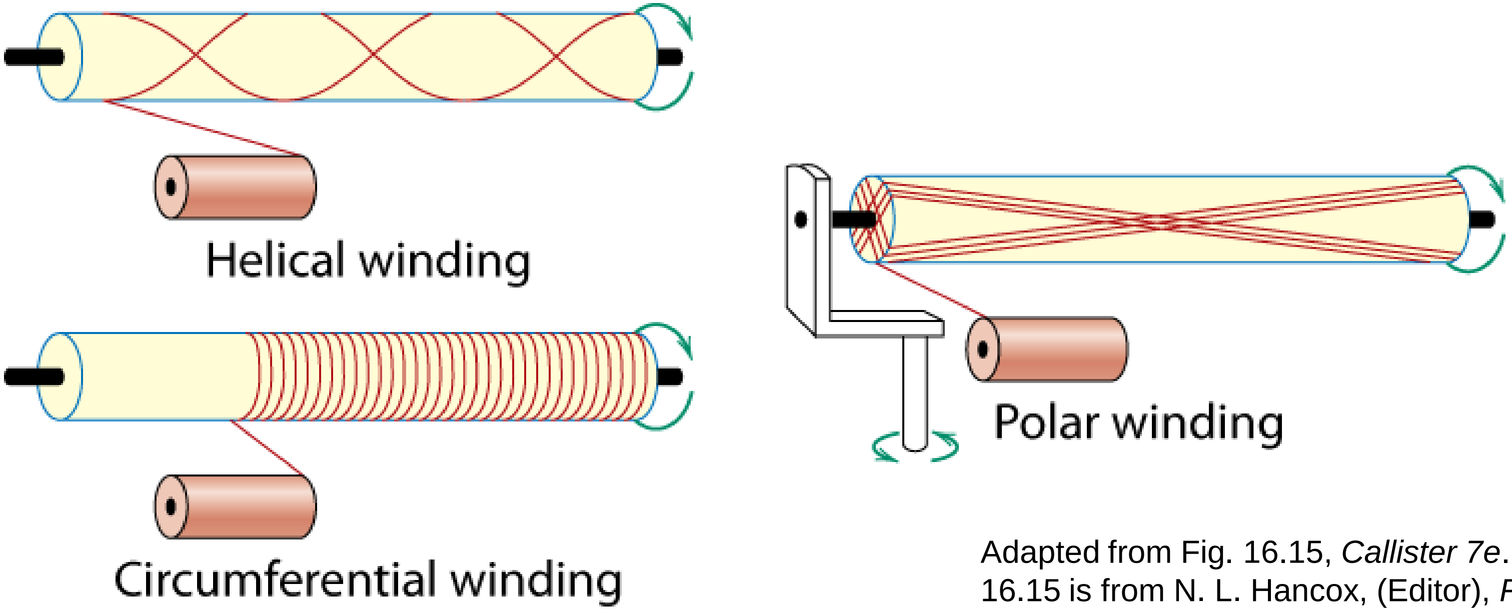


Tape-Laying Machines (Automated Lay-Up)

Cut and lay the ply or prepreg under computer control and without tension; may allow reentrant shapes to be made.

- Cost is about half of hand lay-up
- Extensively used for products such as airframe components, boats, truck bodies, tanks, swimming pools, and ducts.

- Filament Winding
  - Ex: pressure tanks
  - Continuous filaments wound onto mandrel



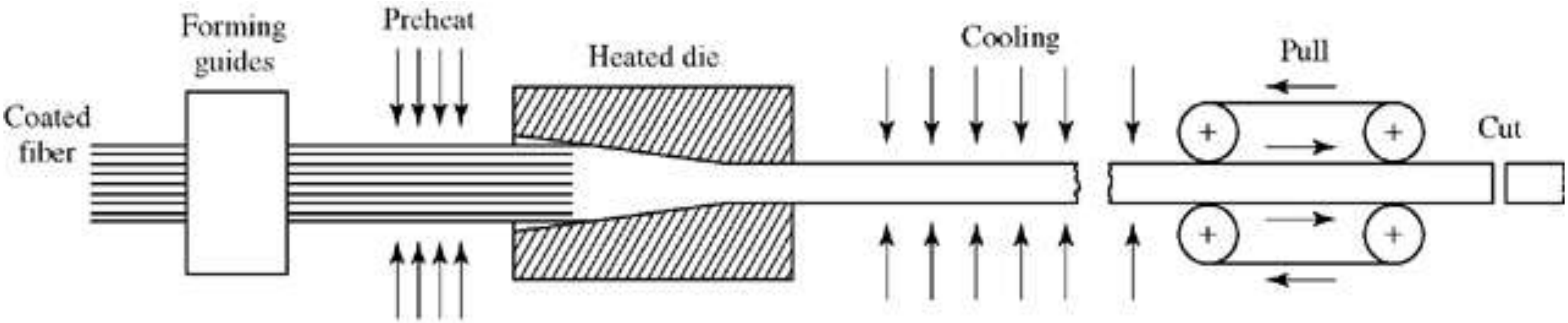
Adapted from Fig. 16.15, *Callister 7e*. [Fig. 16.15 is from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials,* The Macmillan Company, New York, 1981.]

Filament Winding Characteristics

- Because of the tension, reentrant shapes cannot be produced.
- CNC winding machines with several degrees of freedom (sometimes 7) are frequently employed.
- The filament (or tape, tow, or band) is either precoated with the polymer or is drawn through a polymer bath so that it picks up polymer on its way to the winder.
- Void volume can be higher (3%)
- The cost is about half that of tape laying
- Productivity is high (50 kg/h).
- Applications include: fabrication of composite pipes, tanks, and pressure vessels. Carbon fiber reinforced rocket motor cases used for Space Shuttle and other rockets are made this way.

Pultrusion

- Fibers are impregnate with a prepolymer, exactly positioned with guides, preheated, and pulled through a heated, tapering die where curing takes place.

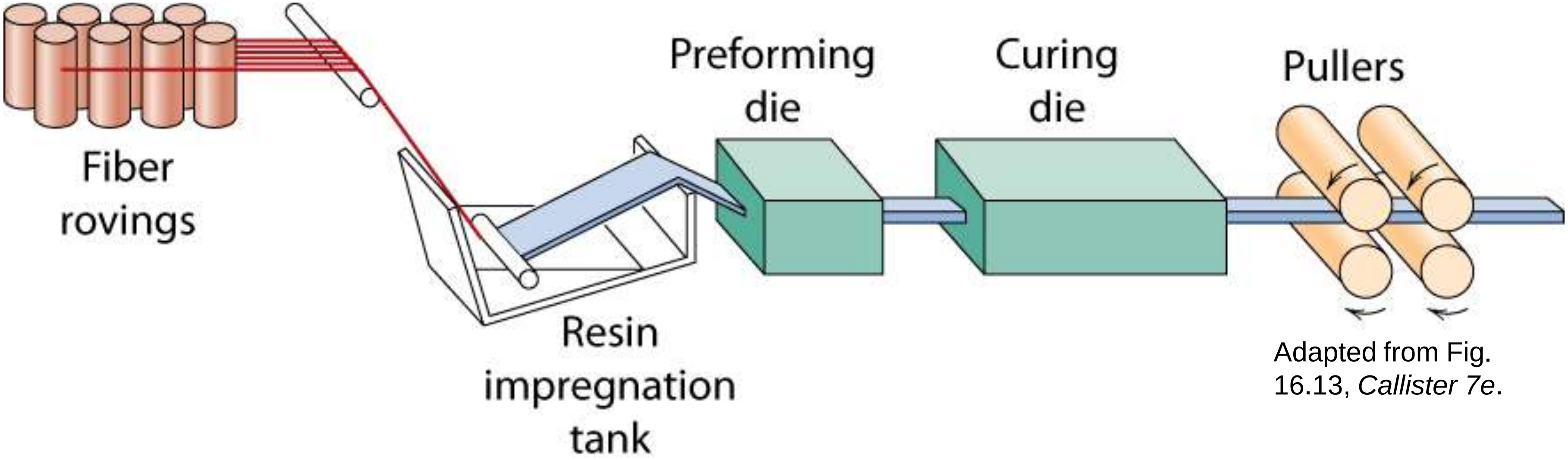


- Emerging product is cooled and pulled by oscillating clamps
- Small diameter products are wound up
- Two dimensional shapes including solid rods, profiles, or hollow tubes, similar to those produced by extrusion, are made, hence its name ‘pultrusion’

Composite Production Methods

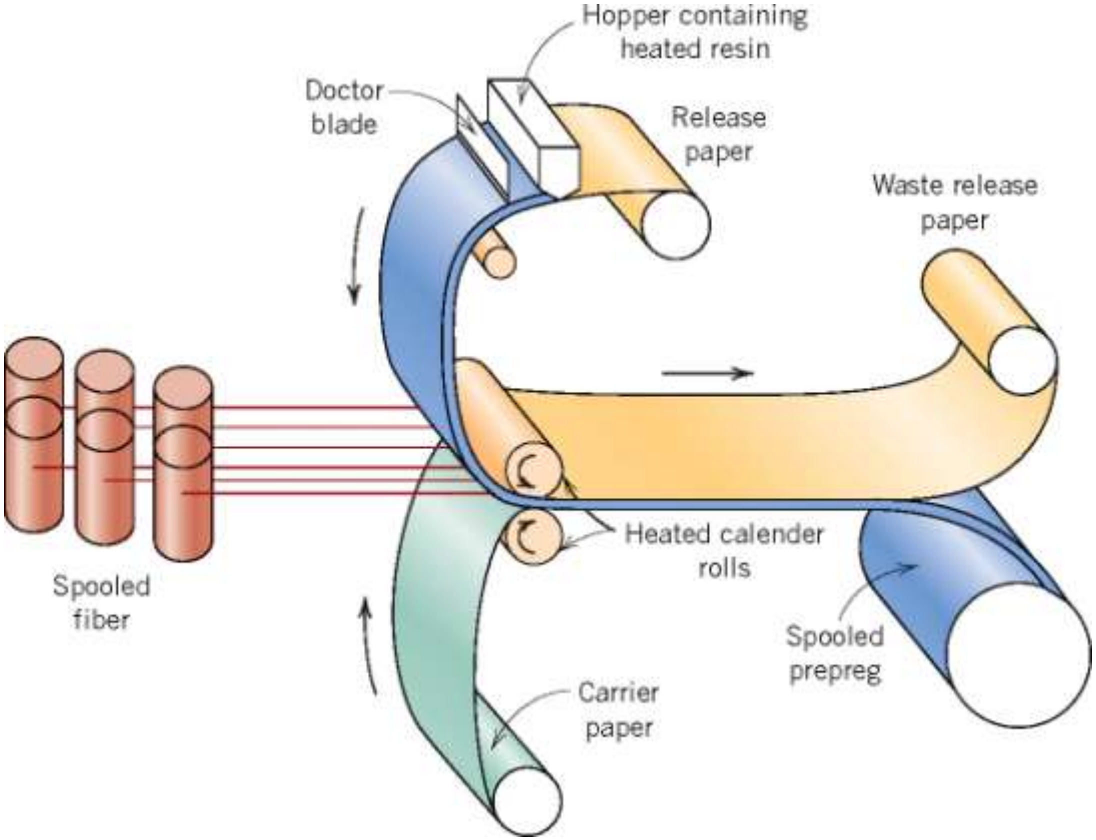
Pultrusion

- Continuous fibers pulled through resin tank, then preforming die & oven to cure



Adapted from Fig. 16.13, *Callister 7e*.

- Production rates around 1 m/min.
- Applications are to sporting goods (golf club shafts), vehicle drive shafts (because of the high damping capacity), nonconductive ladder rails for electrical service, and structural members for vehicle and aerospace applications.



PREPREG PRODUCTION PROCESSES

- Prepreg is the composite industry's term for continuous fiber reinforcement pre-impregnated with a polymer resin that is only partially cured.
- Prepreg is delivered in tape form to the manufacturer who then molds and fully cures the product without having to add any resin.
- This is the composite form most widely used for structural applications

PrePreg Process

- Manufacturing begins by collimating a series of spool-wound continuous fiber tows.
- Tows are then sandwiched and pressed between sheets of release and carrier paper using heated rollers (calendering).
- The release paper sheet has been coated with a thin film of heated resin solution to provide for its thorough impregnation of the fibers.

PrePreg Process

- The final prepreg product is a thin tape consisting of continuous and aligned fibers embedded in a partially cured resin
- Prepared for packaging by winding onto a cardboard core.
- Typical tape thicknesses range between 0.08 and 0.25 mm
- Tape widths range between 25 and 1525 mm.
- Resin content lies between about 35 and 45 vol%

PrePreg Process

- The prepreg is stored at 0°C (32 °F) or lower because thermoset matrix undergoes curing reactions at room temperature. Also the time in use at room temperature must be minimized. Life time is about 6 months if properly handled.
- Both thermoplastic and thermosetting resins are utilized: carbon, glass, and aramid fibers are the common reinforcements.
- Actual fabrication begins with the lay-up. Normally a number of plies are laid up to provide the desired thickness.
- The lay-up can be by hand or automated.

Summary

- Composites are classified according to:
  -- the matrix material (CMC, MMC, PMC)
  -- the reinforcement geometry (particles, fibers, layers).
- Composites enhance matrix properties:
  -- MMC: enhance σ_y, *TS*, creep performance
  -- CMC: enhance K_c
  -- PMC: enhance *E*, σ_y, *TS*, creep performance
- Particulate-reinforced:
  -- Elastic modulus can be estimated.
  -- Properties are isotropic.
- Fiber-reinforced:
  -- Elastic modulus and *TS* can be estimated along fiber dir.
  -- Properties can be isotropic or anisotropic.
- Structural:
  -- Based on build-up of sandwiches in layered form.

questions	opt1	opt2	opt3	opt4	opt5	opt6	answer
The materials in which the atoms are arranged in some regu	Crystalline	Non-crystalline	Amorphous	None of the			Crystalline materials
An example for amorphous material is	All metals	Ceramics	Glass	None of the			Glass
Coordination number of Simple Cubic Lattice is	4	6	8	12			4
The capacity of a material to undergo deformation under ter	Mechanical	Stiffness	Toughness	Ductility			Ductility
Study of atomic structure of metals is useful	To understand	To understand	To understand	All of the above			All of the above
Large angle grain boundary defects are associated with	Point defects	Line defects	Surface defects	Volume defects			Surface defects
Point defects are related to	Tilt boundary/	Voids/ stacking	Self interstitials	Edge dislocations			Self interstitials & vacancy
Line defects are related to	Tilt boundary/	Voids/ stacking	Self interstitials	Edge dislocations			Edge dislocations
Surface defects are related to	Tilt boundary/	Voids/ stacking	Self interstitials	Edge dislocations			Tilt boundary/ twist boundary
Volume defects are related to	Tilt boundary/	Voids/ stacking	Self interstitials	Edge dislocations			Voids/ stacking faults
The crystal structure of Silver is	FCC	BCC	HCP	None of the			FCC
A chemically and structurally homogeneous portion of a mi	Phase	Compound	Solid solution	None of the			Phase
-------------------- means that the properties are same in all	Polymorphism	Allotropy	Isotropy	None of the			Isotropy
Alloying is carried out to improve the strength and hardness	Pure metal	Solid solutions	Intermediate	Solid solution or			Solid solution or an
Name the rule which determines solid solubility	Gibbs rule	Hall-petch effect	Hume-Rothery	Both a and b			Hume-Rothery rule
If the atomic sizes of solute and solvent differ by less than -	0.2	0.15	0.3	0.1			0.15
When one element is electronegative and the other electropo	Substitutional	Intermediate	There is no such				Intermediate phase
Gibbs phase rule is given by the equation	P+F=C+1	P+F=C	F=P-C+2	P+F=C+3			P+F=C+1
The important information that can be gathered from phase	Number of	Composition of	Amount of each	All of the above			All of the above
The degrees of freedom in a system are	Temperature	Pressure	Composition	All of the above			All of the above
The phase reaction in which a liquid reacts with a solid to p	Isomorphous	Eutectic reaction	Eutectoid	Peritectic			Peritectic reaction
When a liquid on cooling produces two different solids, it i	Isomorphous	Eutectic reaction	Eutectoid	Peritectic			Eutectic reaction
When a liquid on cooling gives a solid and vice versa, the re	Isomorphous	Eutectic reaction	Eutectoid	Peritectic			Isomorphous reaction
A typical example of an isomorphous system is the	Cu-Ni system	AgPt system	PbSn system	Fe3C system			Cu-Ni system
Solid state reaction is	Isomorphous	Eutectic reaction	Eutectoid	Peritectic			Eutectoid reaction
The chemical composition of the phase is determined by	Lever rule	Drawing a tie line	Gibbs phase rule	None			Drawing a tie line
Electron compounds have	High ductility	Low ductility and	Low ductility and	High ductility			High ductility and low hardness
One example of an electron compound is	Cu-Zn	Mg3Sb2	TiN	WC			Cu-Zn
An example of an Interstitial Compound is	Ti-N	WC	Ta-C	All of the given			All of the given options
Pearlite is the eutectoid mixture of	Ferrite 85% and	Ferrite 87.5%	Ferrite 86% and	Ferrite 86.5%			Ferrite 87.5% and Cementite
Ledeburite is the mixture of	Ferrite and	Ferrite and	Austenite and	Austenite and			Austenite and Cementite
Mild Steel belongs to the following category	Low carbon steel	Medium carbon	High carbon steel	Alloy steel			Low carbon steel
Recrystallization temperature is one	at which crystals	at which new	when a strained	at which change			at which new spherical crystals
Delta iron occurs at a temperature of	room temperature	above melting	between 1400	between 910			between 1400 degree celcius
Which of the following constituents of steel is softest and le	austenite	pearlite	ferrite	cementite			ferrite
Which of the following represents the allotropic forms of ir	alpha, beta and	alpha and beta	body centered	alpha iron,			alpha iron, gamma iron and
Gamma iron exists at following temperature	room temperature	above melting	between 1400	between 910			between 910 degree and 1400
Cast iron is characterized by minimum of following percent	0.002	0.008	0.02	0.043			0.02
Eutectoid steel contains following percentage of carbon	0.0002	0.003	0.0063	0.008			0.008
Basic constituents of Monel metal are	nickel, copper	nickel,	copper, zinc	copper, silver			nickel, copper
Melting point of iron is	1489 degree	1539 degree	1601 degree	1250 degree			1539 degree celcius
Most of the cutting tools are mady of	Low carbon steel	Medium carbon	High carbon steel	None of the			High carbon steel
Nails and screws are made of	Low carbon steel	Medium carbon	High carbon steel	None of the			Low carbon steel
Connecting rod is usually made of	Low carbon steel	Medium carbon	High carbon steel	None of the			Medium carbon steel
Pearlite is the combination of	ferrite and	cementite and	ferrite and	cementite and			ferrite and cementite
Presence of sulphur makes steel brittle. Its effect can be red	copper	magnesium	Manganese	silicon			Manganese
The temperature and carbon content at which eutectic reacti	723°C and 0.02	1130°C and 2.00	1130°C and 4.3	910°C and 4.3 %			910°C and 4.3 % C
The temperature and carbon content at which eutectoid reac	723°C and 0.02	723°C and 0.8 %	1130°C and 4.3	910°C and 4.3 %			723°C and 0.8 % C
Steels are primarily designated according to	iron content	carbon content	alloying elements	none of the above			alloying elements
Sorbite is the structure obtained by	quenching	quenching	quenching	quenching			quenching austenite
Which of the following metals can be easily drawn into wir	cast iron	tin	zinc	copper			copper

questions	opt1	opt2	opt3	opt4	opt5	opt6	answer
The purpose of alloying is to	To increase harden ability.	To improve strength at	To increase corrosion ar	All of the above.			All of the above.
The general effects of alloyin	Carbide formation.	Solid solution formatio	Shifting of critical temp	All of the above.			All of the above.
The effect of adding Boron	It improves wear resistanc	It improves hardenabili	It improves hot hardnes	It improves machinability.			It improves hardenability.
The effect of adding Lead i	It improves wear resistanc	It improves hardenabili	It improves hot hardnes	It improves machinability.			It improves machinability.
The effect of adding Cobal	It improves wear resistanc	It improves hardenabili	It improves hot hardnes	It improves machinability.			It improves hot hardness.
The effect of adding Chron	Improves wear, corrosion	It improves toughness.	It improves hot hardnes	It improves machinability.			Improves wear, corrosion resistance and hardenability.
The effect of adding Nicke	Improves wear, corrosion	It improves toughness.	It improves hot hardnes	It improves machinability.			It improves toughness.
Ferritic Stainless steels ar	Hardening.	Tempering.	Cold working.	Normalizing.			Cold working.
Ferritic Stainless steels ar	low carbon content.	These contain upto 25	Theya are magneti	All of the above.			All of the above.
Martensitic stainless steels	25% and 2 %.	12% and 1.5 %.	18% and 1%.	None of the above.			18% and 1%.
Surgical instruments are m	Ferritic stainless steel.	Martensitic stainless st	Austenetic stainless ste	Duplex stainless steel.			Martensitic stainless steel.
Stainless steels which are	Martensitic stainless steel.	Ferritic stainless steel.	Austenetic stainless stee	Duplex stainless steel.			Austenetic stainless steel.
Tool steels used for makin	High speed steels.	Cold work tool steels.	Hot work tool steels.	Shock resisting tool steels.			Cold work tool steels.
Tool steels which require g	High speed steels.	Cold work tool steels.	Hot work tool steels.	Shock resisting tool steels.			Shock resisting tool steels.
Tool steels used for cutting	High speed steels.	Cold work tool steels.	Hot work tool steels.	Shock resisting tool steels.			High speed steels.
Alloy steels with a good st	Maraging steels.	HSLA steels.	Special alloy steels	None of the above.			HSLA steels.
Ultrahigh strength steels (	Maraging steels.	HSLA steels.	Special alloy steels	None of the above.			Maraging steels.
Cast irons which are easily	White cast iron.	Grey cast iron.	Malleable cast iron.	Nodular cast iron.			Nodular cast iron.
Malleabilization treatment	White cast iron.	Grey cast iron.	Malleable cast iron.	Nodular cast iron.			White cast iron.
White cast iron is extremel	It has higher carbon conte	It has a higher tensile s	All the carbon is in the	None of the above.			All the carbon is in the combined form.
Carbon appears in the free	White cast iron.	Grey cast iron.	Malleable cast iron.	Nodular cast iron.			Grey cast iron.
Castings in which the oute	White cast iron.	Grey cast iron.	Malleable cast iron.	Chilled cast iron			Chilled cast iron
Ni-resist cast iron belongs	Alloy cast iron.	Grey cast iron.	Malleable cast iron.	Nodular cast iron.			Alloy cast iron.
Railway car wheels , crush	White cast iron.	Chilled cast iron.	Malleable cast iron.	Nodular cast iron.			Chilled cast iron.
Steels containing very sma	Maraging steels.	Alloy steels.	Dual phase steels.	Micro alloyed steels.			Micro alloyed steels.
Steels used for making die	Maraging steels.	Mould steels.	Dual phase steels.	Micro alloyed steels.			Mould steels.
Mould steels contain the fo	Cr and Ni.	Cr and V.	Ni and W.	None of the above.			Cr and Ni.
For hot working applicatio	W,Cr and Mo.	B, V and Mo.	V,Mo,Cr.	All of the above			W,Cr and Mo.
Tool steels that contain the	Maraging steels.	Alloy steels.	Dual phase steels.	High speed steels.			High speed steels.
High carbon high chromiu	Maraging steels.	Cold work tool steels.	Dual phase steels.	Micro alloyed steels.			Cold work tool steels.
Tungsten in high speed ste	hot hardness	toughness	wear resistance	sharp cutting edge			hot hardness
Which of the following con	austenite	pearlite	ferrite	cementite			ferrite
The percentage of carbon i	0.5 % to 1 %	1 – 2%	2.5 – 4.5 %	5 – 7%			2.5 – 4.5 %
Unique property of cast iro	malleability	ductility	surface finish	damping characteristics			damping characteristics
Cast iron is characterized b	0.20%	0.80%	1.30%	2%			2%
Copper-Zinc alloy is ------------	brass	bronze	lead	zinc			brass
Bronze is an alloy of	copper and zinc	copper and tin	copper, tin and zinc	all of the given options			copper and tin
Monel is an ------------- alloy	aluminium – zinc	nickel – copper	aluminium- silicon – ma	aluminium- silicon alloy			nickel – copper
------------ is used for making g	tin	zinc	aluminium	copper			zinc
-------- is mainly used for stora	lead	zinc	aluminium	copper			lead
The recrystallisation temperat	sulphur	silicon	antimony	vanadium			antimony
------------ is used for making n	kovar	invar	alnico	permalloy			invar
------------- is the composition	60% cu, 40% zn	40%cu, 60% zn	80% cu , 20 %zn	20% cu , 80% zn			60% cu, 40% zn
Which of the following is usec	duralumin	aluminium bronze	gun metal	silicon bronze			aluminium bronze
Magnesium alloys are	highly machinable	light	resistant to corrosion	magnetic			light
Hast alloy consists of	copper and nickel	copper and aluminium	molybdenum and nicke	nickel and aluminium			molybdenum and nickel
Aluminium alloy commonly us	duralumin	y-alloy	babbit alloy	hindalium			hindalium
Manganese in steel increases	tensile strength	hardness	ductility	fluidity			tensile strength
Sulphur in steel	acts as deoxidizer	reduces the grain size	decreases tensile streng	lowers the toughness and transverse ductil			lowers the toughness and transverse ductility
Chromium in steel	improves wear resistance,	refines grain size and	improves cutting ability	makes steel hard			improves wear resistance, cutting ability and toughness

questions	opt1	opt2	opt3	opt4	opt5	opt6	answer
The tendency of the brittle fracture is increased with	decreasing tempe	increasing tempe	increasing and decrea	All of the above			decreasing temperature
Griffith theory is valid only to	ductile material	brittle material	both (a and (b	none of the above			brittle material
------------ fracture is called cup- and -cone fracture	ductile fracture	brittle fractur	fatigue fracture	creep fracture			ductile fracture
--------- materials are often used for compression tests	ductile material	brittle materi	both (a and (b	none of the above			brittle material
The total energy absorbed by the materials before fracturing is called	stiffness	ductility	toughness	malleability			toughness
The property of a material by virtue of which it resists deformation is	creep	toughness	hardness	stiffness			stiffness
The property of material by virtue of which it can withstand varying s	impact streng	resilience	endurance	none of the above			endurance
The plastic deformation in crystalline materials occurs at temperature	0.4 tm	Above 0.4 Tı	Below 0.4 Tm	All of the above			0.4 tm
The tendency of the brittle fracture increases with	increasing str	decreasing st	no change in strain ra	both increasing and decreasing strain rate			increasing strain rate
Hardness is the property of material by virtue of which it is able to re:	force and inte	abrasion and	force and abrasion	fracture			abrasion and intendation
Materials having fine grain structure will have	high yield str	high yield str	high hardness	none of the above			high yield strength, high tensile strength and high hardness
The slip occurs by	rotational mo	sliding of the	translatory motion al	all of the above			translatory motion along sliding planes and rotation of the specimen
Twinning occurs due to	sliding of pla	presence of d	material defects	growth and movement of dislocations in the crystal lattice			growth and movement of dislocations in the crystal lattice
Fracture is caused due to	excessive loa	cracks	material deformation	action of stresses			cracks
In crystalline material the fracture takes place normal to the specific c	slipping plan	twinning plai	cleavage plane	fracture plane			cleavage plane
Ductile fracture occurs by	compressive l	presence of c	slow tearing of metal	all of the above			slow tearing of metals
Fatigue fracture occurs at stresses	below the ten	above the ten	at the tensile stress of	at the shear load			below the tensile stress of the material
Secondary creep is usually termed as	instaneous el	steady state c	recovery effect	none of the above			steady state creep
Which of these belongs to non- destructive testing	tensile test	impact test	fatigue test	ultrasonic test			ultrasonic test
Which of these belongs to destructive testing	ultrasonic tes	liquid penetra	magnetic particle test	tensile test			tensile test
If BHN value is higher then the material is said to be	soft material	hard material	tougher material	none of the above			hard material
Vicker's hardness test is also called as	diamond pyra	static load tes	Rockwell hardness te	Indentation test			diamond pyramid hardness test
Indentor used in Rockwell c scale is	square based	tungsten carb	diamond cone	steel ball			diamond cone
Izod test uses a	simply- supp	cantilever sp	hinged specimen	roller – supported specimen			cantilever specimen
When the specimen I fatigue test is rotated using an electric motor	the upper sur	the upper sur	both experiences tens	the specimen breaks			the upper surface is subjected to tension and the lower experiences compressio
Rockwell 'C' scale uses minor increment load of 10 kg and the majo	100 kg and 1	140 kg and 1	150 kg and 120 degr	140 kg and 120 degree			140 kg and 120 degree
On Rockwell'C' scale, one Rockwell number is represented by penet	0.0080 inch	0.00080 in	0.000080 inch	0.0000080 inch			0.000080 inch
Brinell tester uses a hardness steel ball of size	1 mm	5 mm	10 mm	15 mm			10 mm
Moh's scale is used in connection with	composition of m	hardness c	wear criterion of m	tensile strength of metal			hardness of materials
The hardness number 10 on Moh's scale for hardness is assigned to	quartz	talc	topaz	corundum			topaz
The hardness number 1 on Moh's scale for hardness is assigned to	quartz	talc	topaz	corundum			quartz
Charpy test is conducted to measure	hardness	fracture str	fatigue resistance	brittleness			brittleness
The hardness of lathe bed material should be measured by	Rockwell tester	Brinell hai	Shore scleroscope	Vicker hardness tester			Brinell hardness tester
Choose the wrong statement	Hardness is meas	Copper is m	Silicon carbide is a c	The capacity of a material to withstand deformation under compression withou			The capacity of a material to withstand deformation under compression witho
When a material is subjected to fluctuating or repeated stresses, fract	creep	fatigue	impact	malleability			fatigue
When a material sustains steady loads for long periods of time, the m	creep	fatigue	impact	malleability			creep
The capacity of a metal to exhibit considerable elastic recovery upon ı	toughness	hardness	stiffness	resilence			resilence
In case of Rockwell hardness test as compared to Brinell hardness tes	indenters and loa	indenters a	indenters are larger	indenters are smaller but loads are larger.			indenters and loads are smaller
A test, used to determine the behaviour of materials when subjected t	hardness test	impact test	Fatigue test	Torsion test			impact test
The Brinell Hardness Number for mild steel approximately lies in the	50 to 70	70 to 100	110 to 150	150 to 300			110 to 150
The Brinell Hardness number for soft brass approximately lies in the	50 to 70	70 to 100	110 to 150	150 to 300			50 to 70
In a Rockwell test, for testing hardness of alloy cast iron generally	scale B is used	scale C is u	both scales are use	none of the above			scale C is used
The rollers of a cycle chain are subjected to following type of stress	compressive	tensile	bending	fatigue			fatigue
The most notable precipitation hardenable alloys are those in which tl	copper	nickel	manganese	aluminium			nickel
The offset yield strength is often referred to as	ultimate tensile s	breaking st	proof stress	none of the above.			proof stress
Scratch hardness is	the resistance off	reistance of	resistance offered b	none of the above			the resistance offered by the material to scratching
Rebound hardness is	the resistance off	reistance of	resistance offered b	none of the above			reistance of the material to strike and rebound
Rebound hardness is measured by an instrument called	creep tester	universal test	scleroscope	none of the above.			scleroscope
Creep data are important for	polymer material	metallic a	composite materia	none of the above.			metallic and ceramic materials
In creep curve, during the first stage of creep,	creep rate decrea	creep rate is li	creep prate increases v	none of the above.			creep rate decreases with time

questions	opt1	opt2	opt3	opt4	opt5	opt6	answer
The Temperature at which the hypoeutec	between 723C and 910	above 910C	below 723C	none of the above			between 723C and 910 C
The resulting structure of hypoeutectoid	pearlite with cementite	pearlite with ferrite	ferrite with cementite	ferrite with martensite			pearlite with ferrite
The resulting structure of hyper eutectoi	pearlite with ferrite	ferrite with cementite	pearlite with cementi	none of the above			pearlite with cementite
provides a fine grain structure	full annealing	normalizing	tempering	none of the above			normalizing
The low temperature tempering is perfor	350C to 450C	150C to 250C	500C to 600C	none of the above			150C to 250C
The tempering which is performed in the	low temperature temperi	medium temperat	high temperature	none of the above			medium temperature tempering
The structure formed after normalizing f	ferrite and pearlite	ferrite and cementite	austentite and cemen	pearlite and cementite			ferrite and pearlite
The structure formed after normalizing	Ferrite and pearlite	Ferrite and cementite	Ferrite and cementite	Pearlite and cementite			Pearlite and cementite
The structure formed after austempering	Bainite	Pearlite	Cementite	Ferrite			Bainite
Selecting of temperature for heat treatme	Fe – Fe3C phase diagram	TTT diagram	CCT diagram	S – curves			Fe – Fe3C phase diagram
TTT diagram is also called as	isothermal transformation	S curve	all of the listed optio	bains curve			isothermal transformation
Assumption in TTT diagram	Temperature is constant dur	Time is constant duri	Temperature is const	Time is constant in equilibrium			Temperature is constant during transformation
In CCT diaram very slow cooling rate re	coarse pearlite	fine pearlite	pearlite and cementit	granular cementite			coarse pearlite
In CCT diagram more rapid cooling resu	Coarse to fine pearlite	fine to coarse pearlite	bainite	martensite			Coarse to fine pearlite
In CCT diagram if water is quenching m	martensite	bainite	fine bainite	leduburite.			martensite
Critical cooling rate results in slowest rat	100% martensite	50% martensite and 5	25% martensite and	martensite and bainite			100% martensite
Hardening results with	formation of cementite	formation of martensi	formation of bainite	decomposition of austentite			formation of martensite
Corrosion resistance of steel is increased	vanadium, aluminium	tungsten, molybdenu	chromium and nickel	zinc			chromium and nickel
Cyaniding is the process of	dipping steel in cyanide bath	reacting steel surface	adding carbon and ni	obtaining cyanide salts			adding carbon and nitrogen by heat treatment of steel to increase its surface hardness
Induction hardening is the process of	hardening surface of workpi	heating and cooling r	increasing hardness t	hardening core			increasing hardness throughout
Process of austempering results in	formation of bainite structur	carburized structure	martenistic structure	relieving stresses throughout a component			formation of bainite structure
Materials after cold working are subjecte	hot working	tempering	normalizing	annealing			annealing
Which is the false statement about tempe	improve ductility	improve machinabilit	improve toughness	relieve stresses			improve machinability
Which is the false statement about case h	cyaniding	nitriding	electroplating	induction hardening			electroplating
The hardness of steel increases, if it cont	autenite	martensite	pearlite	cementite			martensite
The machinability of steel is increased by	silicon and sulphur	phosphorous, lead an	sulphur, graphite and	phosphorous and aluminium			phosphorous, lead and sulphur
Which one of the following metals work-	copper	brass	lead	silver			brass
Hardenability of steel	is the depth of penetration o	is the ability of steel t	is the property which	is the ability to withstand shocks.			is the property which determines the depth of the hardened zone induced by quenching
The hardest known material is	ceramic	high speed steel	cemented carbide	diamond			diamond
Steels containing high percentage of elen	alloy steels	stainless steels	structural steels	high carbon steels			alloy steels
HSS belongs to the category of	alloy steel	low carbon steel	medium carbon steel	high carbon steel			alloy steel
Large amounts of silicon when added to	mechanical	refractory	corrosive	magnetic			magnetic
Machinability of a metal depends on	hardness	tensile strength	brittleness	both (a) and (b)			both (a) and (b)
Heat treatment operation involving heati	normalising	annealing	hardening	tempering			annealing
Heat treatment operation involving heati	normalising	annealing	stress-relieving	austempering			normalising
Tempering temperature of most of the m	100 - 150°C	200 - 300°C	350 - 400°C	400 - 500°C			350 - 400°C
Normalising operation is carried out in	furnace	water	air	oil			oil
In Nitriding steel components, the follow	inert	liquid nitrogen	carbon	ammonia			ammonia
Pick up the wrong statement. Annealing	refining grain structure	relieving stresses	improving machinabi	improving wear resistance			relieving stresses
After annealing, a non-ferrous metal, sur	removed with coarse emery	pickled in acid and th	left on the metal to p	hammered into the surface			pickled in acid and then removed
The hardening of machine tool guideway	induction hardening	flame hardening	salt bath hardening	vacuum hardening			flame hardening
Austempering is the heat treatment proc	hardness	toughness	softness	brittleness			hardness
To eliminate brittleness which occurs du	annealed	toughened	work hardened	tempered			annealed
Which of the following is not the objecti	refine steel structure	remove strains cause	remove internal stres	improve machine structure			remove internal stresses
The main purpose of heat treatment of st	chemical composition	mechanical propertie	corrosion properties	surface finish			mechanical properties
Low carbon steel can be hardened by	hardening	heating and quenchin	heating and quenchin	carburizing and cyaniding			carburizing and cyaniding
The hardening strains are reduced and th	annealing	carburizing	tempering	anodizing			tempering
Case hardening is the only method suitab	high alloy steel	low carbon steel	medium carbon steel	tungsten carbide			low carbon steel
Which of the following is a case hardeni	spheroidising	tempering	normalising	cyaniding			cyaniding
A big advantage of surface hardening by	it is a mass production proce	it is simple and cheap	parts need not be que	it does not require furnace			parts need not be quenched
Cast iron contains carbon	0.01	less than 1%	more than 8%	none of the above			none of the above
The following structure is obtained by au	Troostite	bainite	martensite	sorbite			bainite
Which is the softest out of the following	ferrite	austenite	cementite	pearlite			ferrite
Warping of articles during heat treatmen	Non-uniform heating	Non-uniform cooling	Internal stresses in th	both (a) and (b)			both (a) and (b)
An operation on steel aimed at softening	softening	cold working	annealing	tempering			annealing
The hardeness obtained by hardening pr	carbon content	atmospheric temperat	work size	quenching time			atmospheric temperature
Identify the process different from other	carburizing	nitriding	galvanising	cyaniding			nitriding
Cold worked components are generally s	hardening	tempering	annealing	carbonitriding			annealing
The process of introducing carbon into l	carburizing	nitriding	carbonitriding	induction hardening			carburizing
Jominy end quench test is used to determ	ductility of steel	tensile strength of ste	hardenability of steel	wear resistance of steel			hardenability of steel