Metals

Part 1

Manufacturing Materials IE251

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Four Types of Engineering Materials

1. Metals
2. Ceramics
3. Polymers
4. Composites

METALS

1. Alloys and Phase Diagrams
2. Ferrous Metals
3. Nonferrous Metals
4. Superalloys
5. Guide to the Processing of Metals

Why Metals Are Important

- High stiffness and strength - can be alloyed for high rigidity, strength, and hardness
- Toughness - capacity to absorb energy better than other classes of materials
- Good electrical conductivity - Metals are conductors
- Good thermal conductivity - conduct heat better than ceramics or polymers
- Cost – the price of steel is very competitive with other engineering materials

Starting Forms of Metals used in Manufacturing Processes

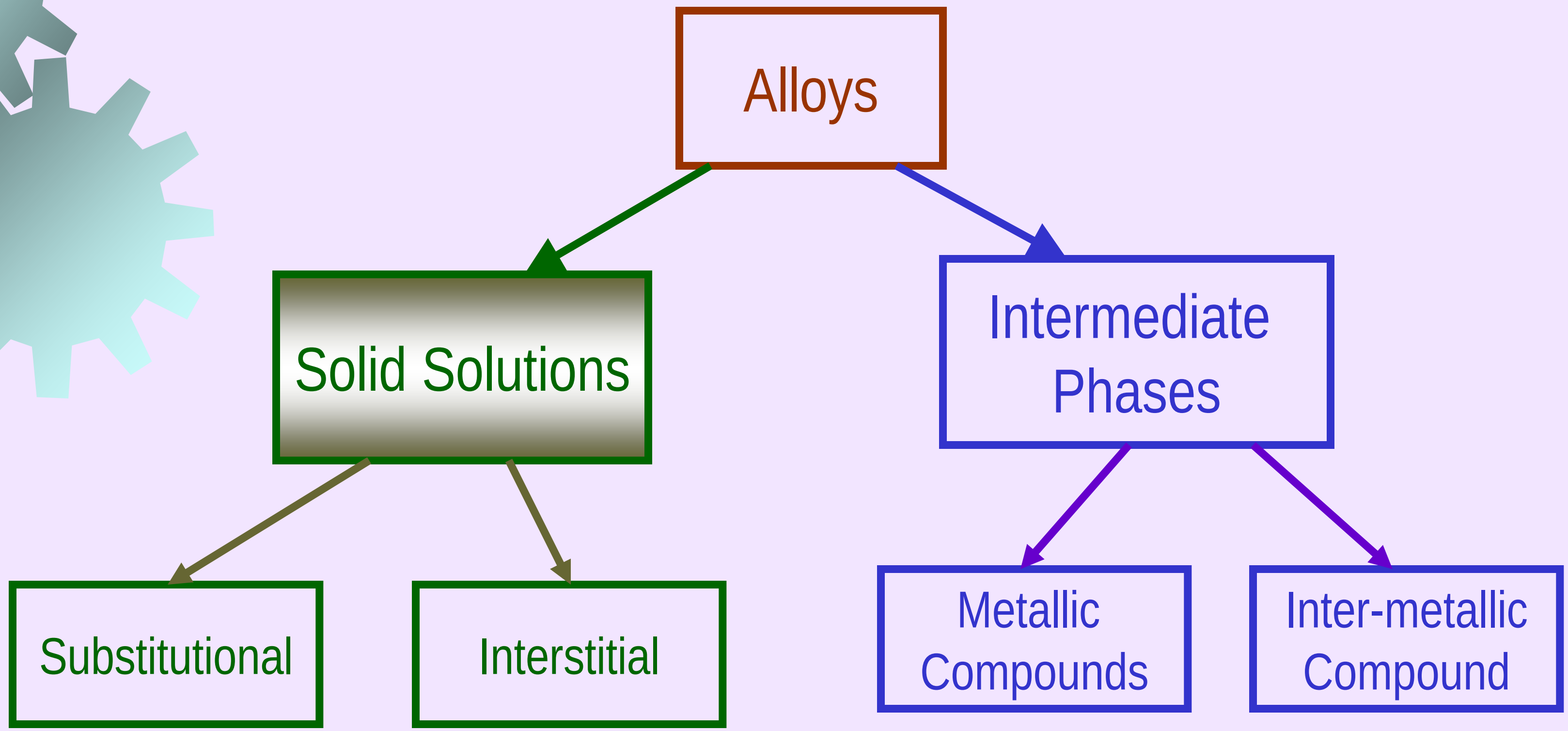
- Cast metal - starting form is a casting
- Wrought metal - the metal has been worked or can be worked after casting
- Powdered metal - starting form is very small powders for conversion into parts using powder metallurgy techniques

Classification of Metals

- *Ferrous* - those based on iron
  - Steels
  - Cast irons
- *Nonferrous* - all other metals
  - Aluminum, magnesium, copper, nickel, titanium, zinc, lead, tin, molybdenum, tungsten, gold, silver, platinum, and others
- Superalloys

Metals and Alloys

- An Alloy = A metal composed of two or more elements
  - At least one element is metallic
- Enhanced properties versus pure metals
  - Strength
  - Hardness
  - Corrosion resistance
- Two main categories
  - Solid Solutions
  - Intermediate Phases


Alloys
Solid Solutions
Intermediate Phases
Substitutional
Interstitial
Metallic Compounds
Inter-metallic Compound

Solid Solutions

An alloy in which one element is dissolved in another to form a single-phase structure

- Base element is metallic (Solvent)
- Dissolved element, metallic or non-metal

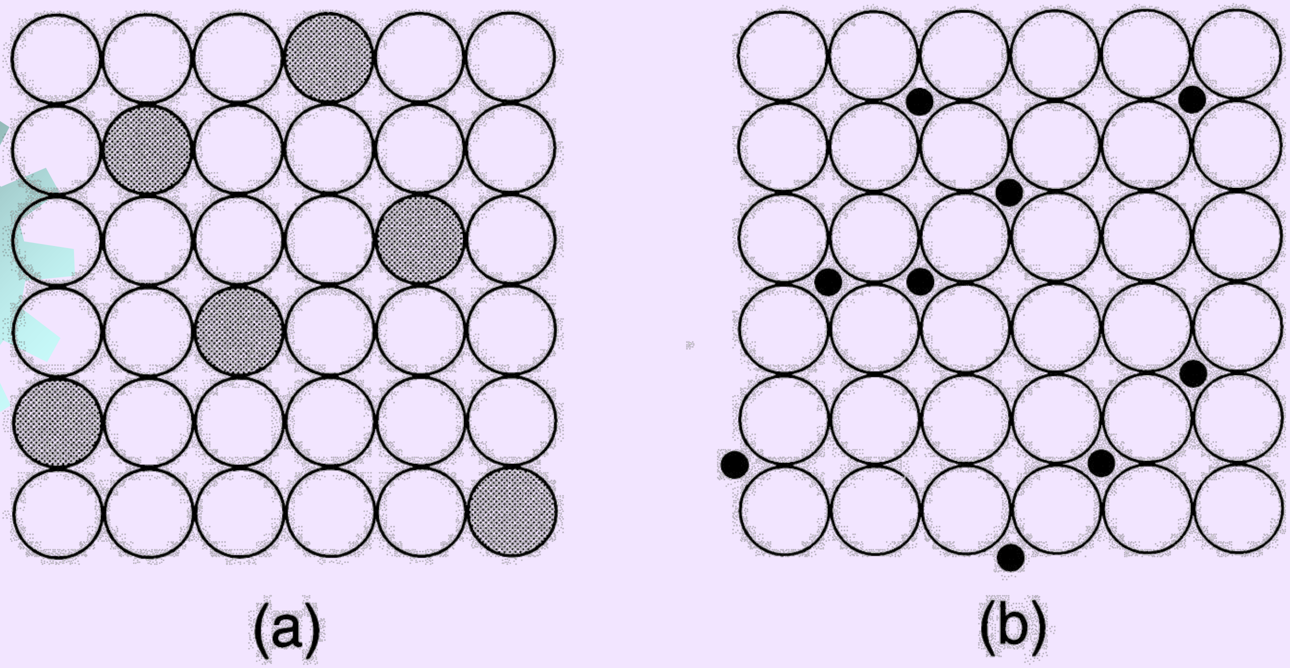
What is a phase (in a material structure)?

A *phase* = any homogeneous mass of material, such as a metal, in which the grains all have the same crystal lattice structure!

Two Forms of Solid Solutions

Atomic radii must be similar

Lower valence metal is usually solvent



Must be small atoms: Hydrogen, Carbon, Nitrogen, Boron

Figure 6.1

Substitutional solid solution - atoms of solvent element are replaced in its unit cell by dissolved element

Interstitial solid solution - atoms of dissolving element fit into vacant spaces between base metal atoms in the lattice structure

In both forms, the alloy structure is generally stronger and harder than either of the component elements

Two Forms of Solid Solutions

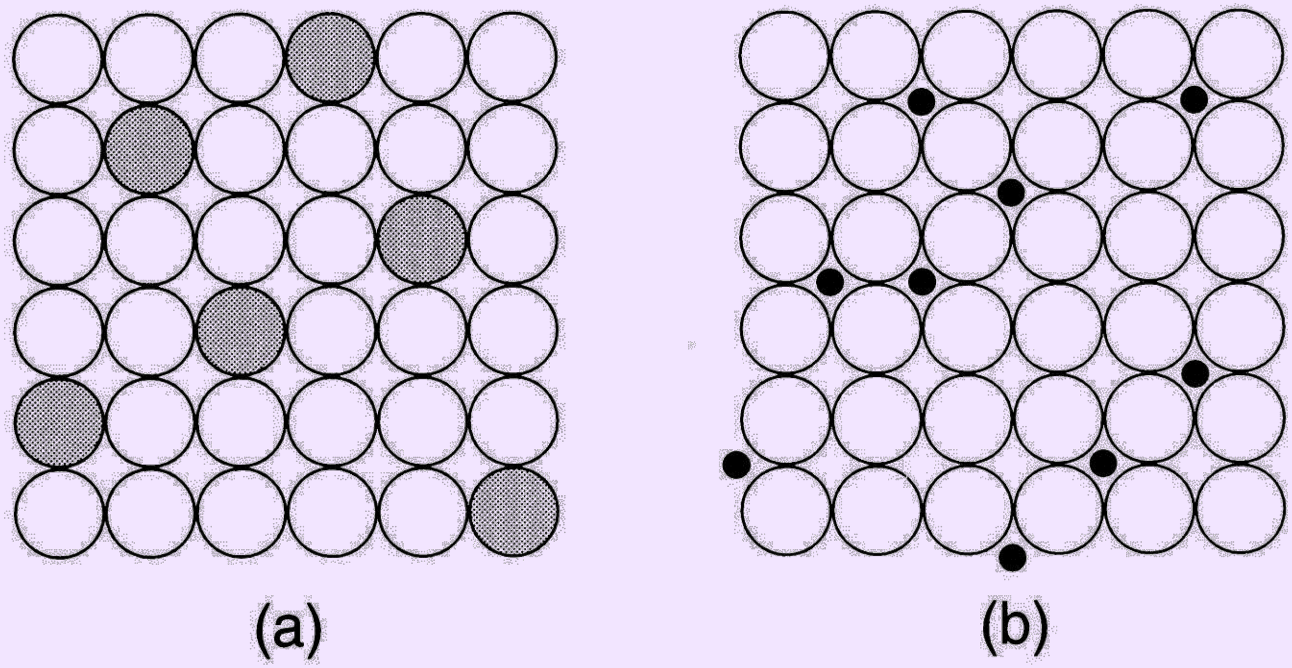


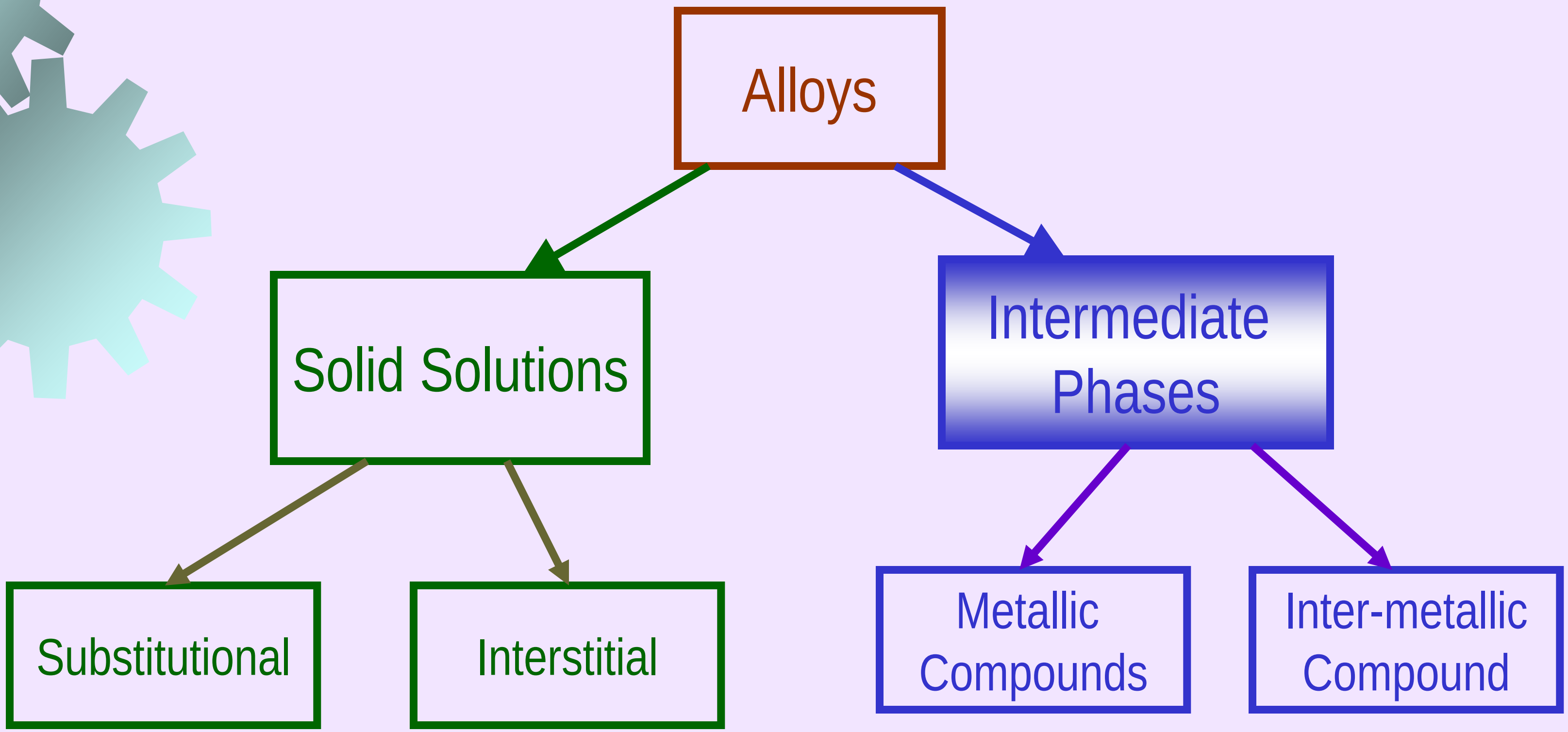
Figure 6.1

Substitutional solid solution

Zinc dissolved in Copper = Brass

Interstitial solid solution

Carbon dissolved in Iron = Steel


Alloys
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Intermediate Phases

- There are usually limits to the solubility of one element in another
- When the amount of the dissolving element in the alloy exceeds the solid solubility limit of the base metal, a second phase forms in the alloy
- The term *intermediate phase* is used to describe it because its chemical composition is intermediate between the two pure elements
- Its crystalline structure is also different from those of the pure metals

Types of Intermediate Phases

1. Metallic compounds – consist of a metal and nonmetal, such as Fe_3C
2. Intermetallic compounds - two metals that form a compound, such as Mg_2Pb

- In some alloy compositions, the intermediate phase is mixed with the primary solid solution to form a two-phase structure
- Some two-phase alloys are important because they can be heat treated for much higher strength than solid solutions

Phase Diagrams

Phase Diagrams

A graphical picture showing the phases of a metal alloy system as a function of composition and temperature

- A phase diagram for an alloy system consisting of two elements at atmospheric pressure is called a *binary phase diagram*
- Composition is plotted on the horizontal axis and temperature on the vertical axis
- Any point in the diagram indicates the overall composition and the phase or phases present at the given temperature under equilibrium conditions

Copper-Nickel (Cu- Ni) Phase Diagram

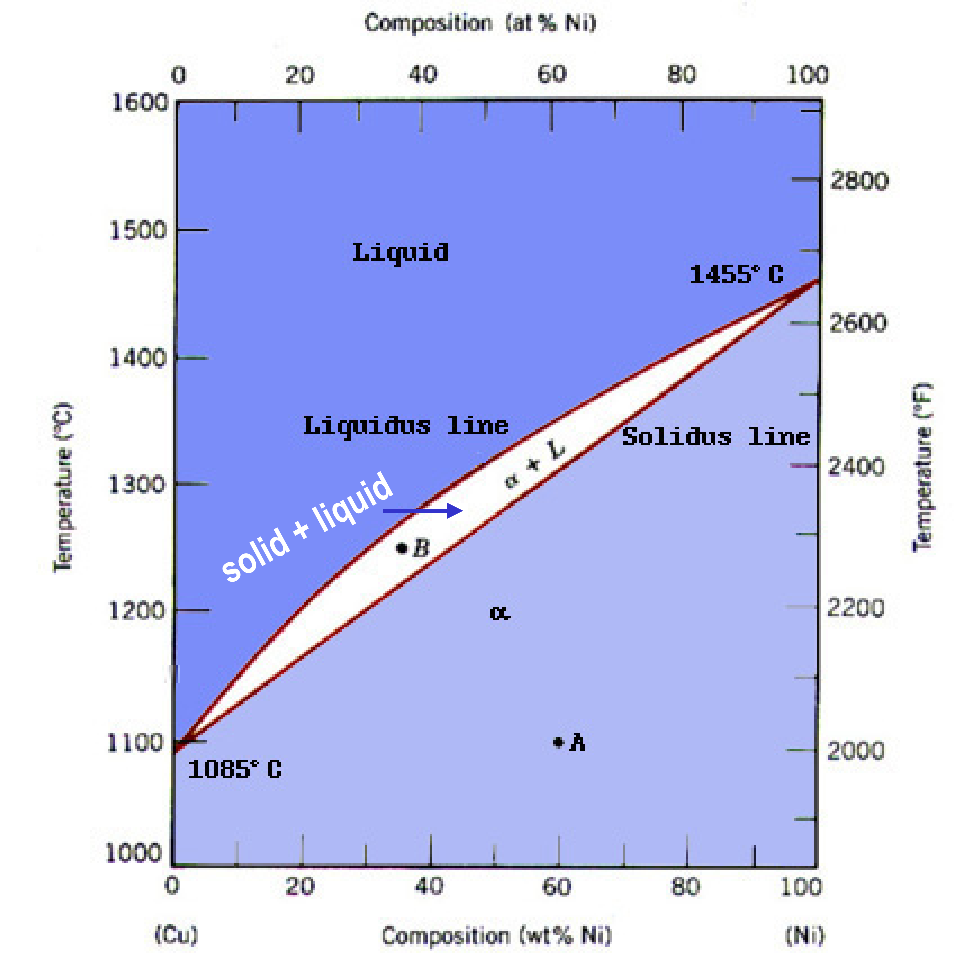


Figure 6.2 Phase diagram for the copper-nickel alloy system.

Consider point A:
Composition: 60% Ni, 40% Cu
At 1100^0 C (or 2000^o F) the alloy is still at solid stage.

Consider point B:
About 35% Ni and 65% Cu,
At 1250^{o}C, it is a mixture of liquid and solid.

Chemical Compositions of Phases

- The overall composition of the alloy is given by its position along the horizontal axis
- However, the compositions of liquid and solid phases are not the same
  - These compositions can be found by drawing a horizontal line at the temperature of interest
  - Where the line intersects the solidus and liquidus indicates the compositions of solid and liquid phases, respectively. We use the Inverse Lever Rule to find the compositions:

Example

Determine compositions of liquid and solid phases in the Cu-Ni system at an aggregate composition of 50% nickel and a temperature of 1260ºC (2300ºF)

- The proportion of solid phase present is given by

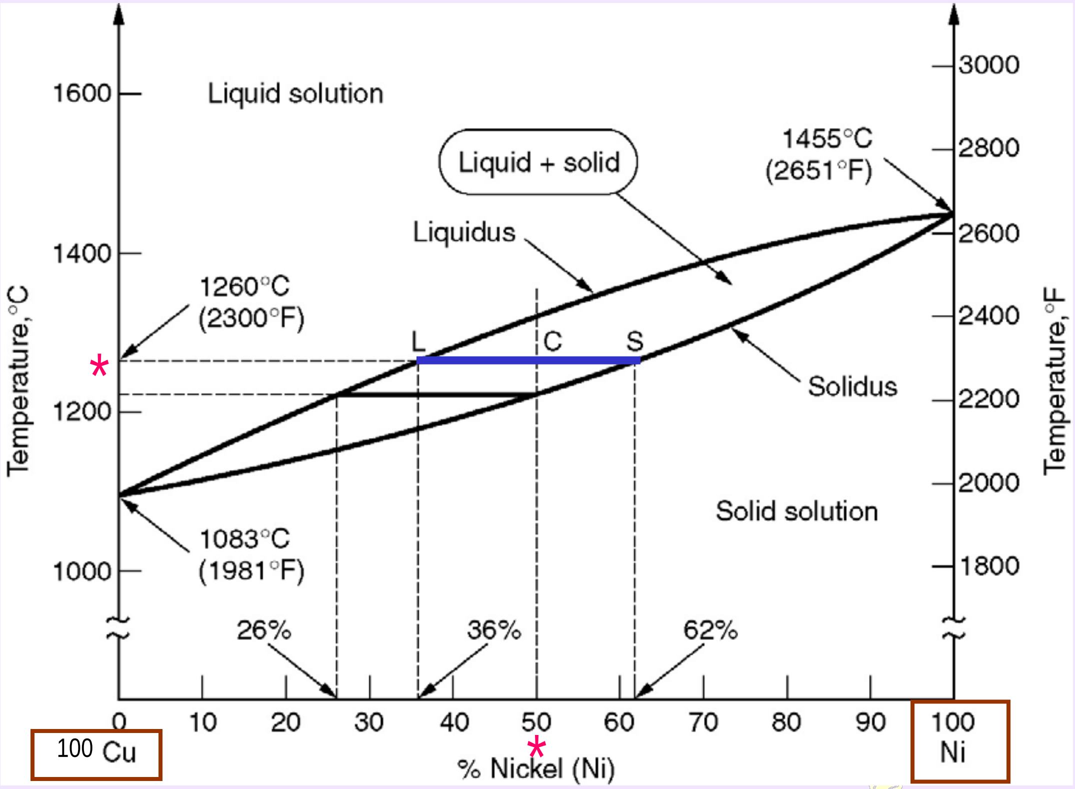
$$\text{S phase proportion} = \frac{CL}{CS + CL}$$

$= (50\text{-}36)/(14+12)=54\%$

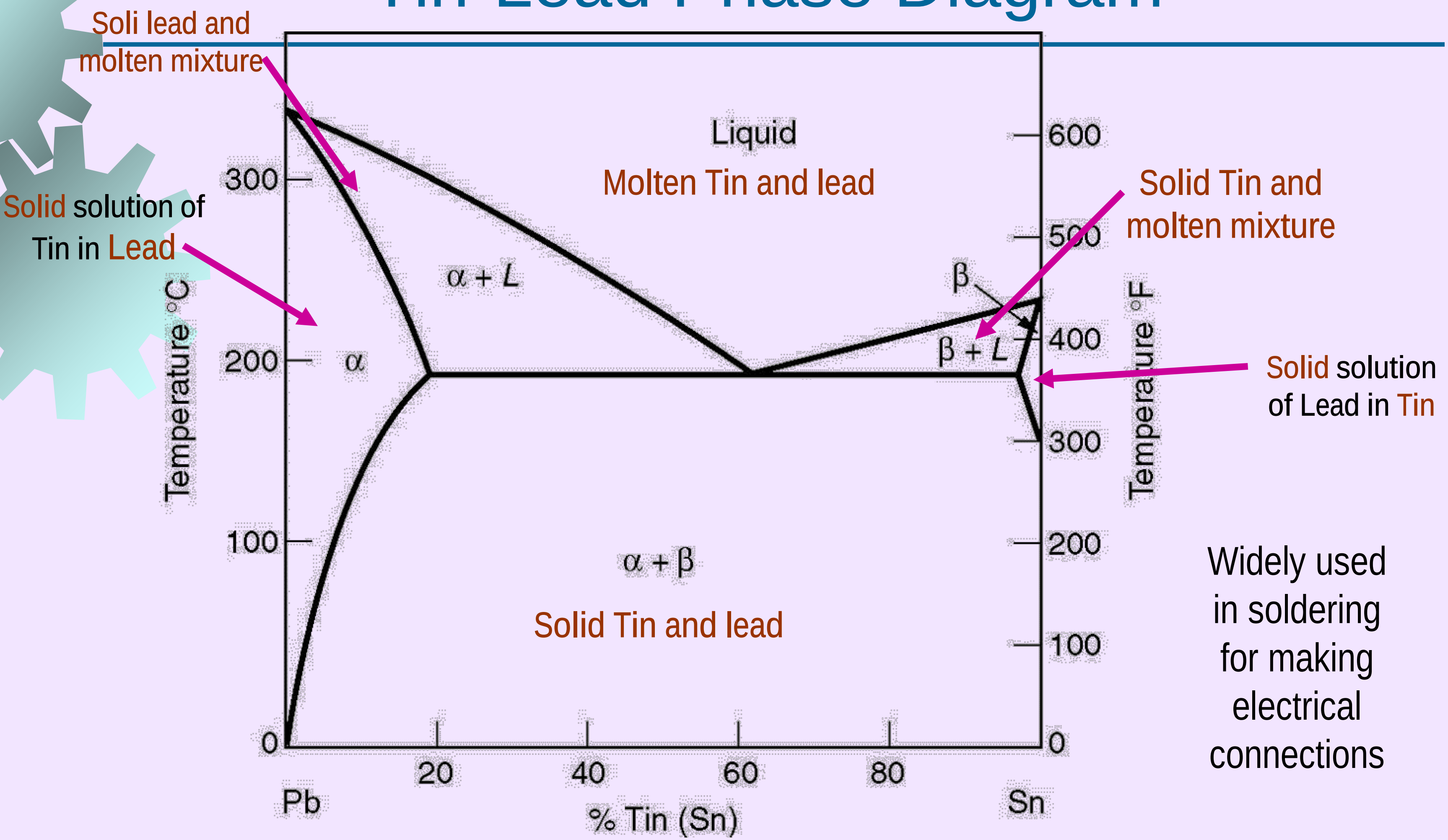
- And the proportion of liquid phase present is given by

$$\text{L phase proportion} = \frac{CS}{(CS + CL)}$$

$= 100\% - 54\% = 46\%$



Tin-Lead Phase Diagram



Widely used in soldering for making electrical connections

Figure 6.3 Phase diagram for the tin-lead alloy system.

Pure tin melts at 232°C (449°F)

Pure lead melts at 327°C (621°F)

Ferrous Metals

Ferrous Metals

Based on iron, one of the oldest metals known to man

- Ferrous metals of engineering importance are alloys of iron and carbon

- These alloys divide into two major groups:
  - Steel
  - Cast iron

- Together, they constitute approximately 85% of the metal tonnage in the United States

Steel and Cast Iron

What is the difference between steel and cast iron?!

Steel and Cast Iron Defined

Steel = an iron-carbon alloy containing from 0.02% to 2.1% carbon

Cast iron = an iron-carbon alloy containing from 2.1% to about 4% or 5% carbon

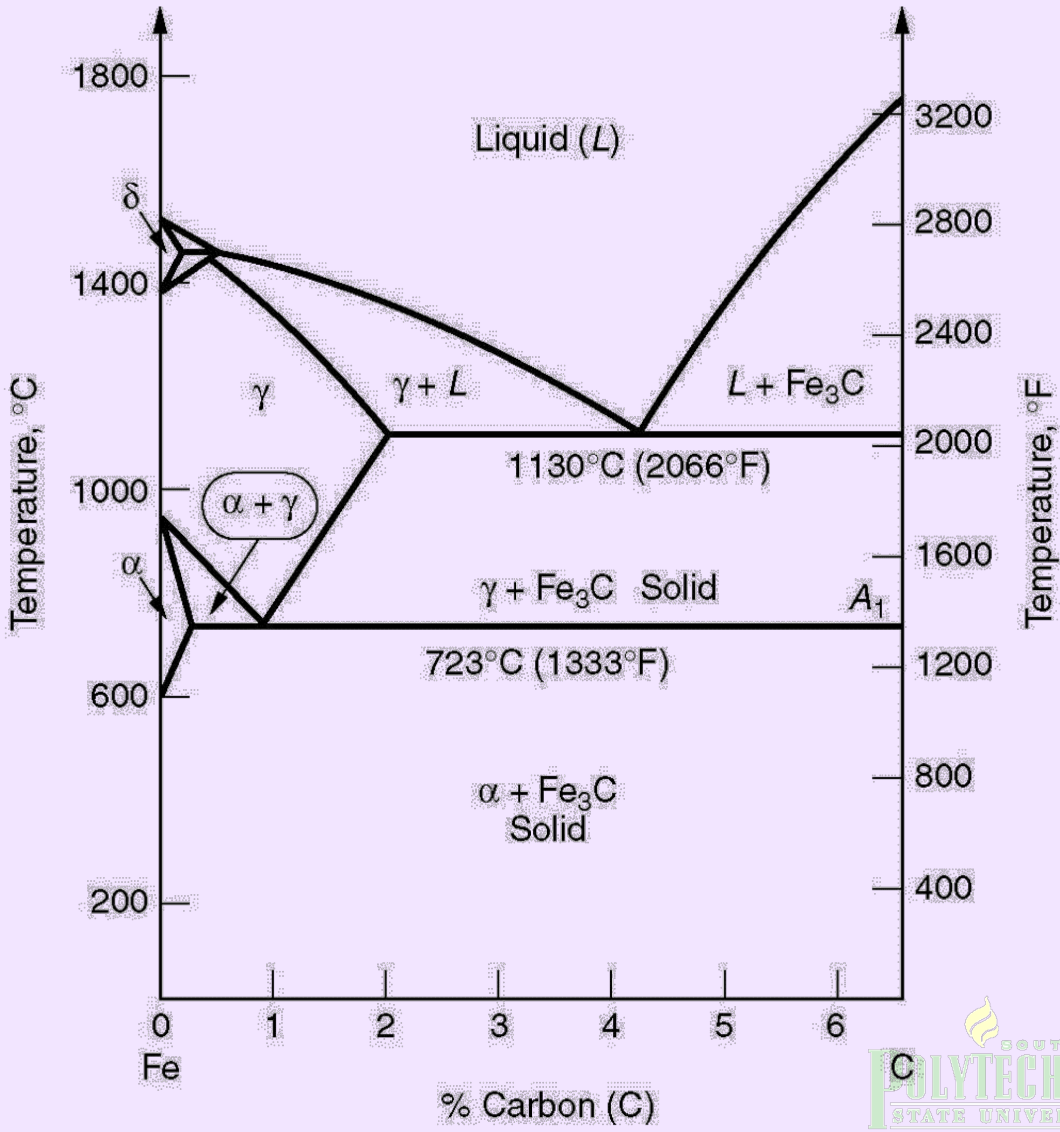
- Steels and cast irons can also contain other alloying elements besides carbon

Iron-Carbon Phase Diagram

Figure 6.4 Phase diagram for iron-carbon system, up to about 6% carbon.

Watch the DVD of the book:

Choose Additional Processes, then Heat treating.



Steel

Steel

An alloy of iron containing from 0.02% and 2.11% carbon by weight

- Often includes other alloying elements: nickel, manganese, chromium, and molybdenum

- Steel alloys can be grouped into four categories:
  1. **Plain carbon steels**
  2. **Low alloy steels**
  3. **Stainless steels**
  4. **Tool steels**

Plain Carbon Steels

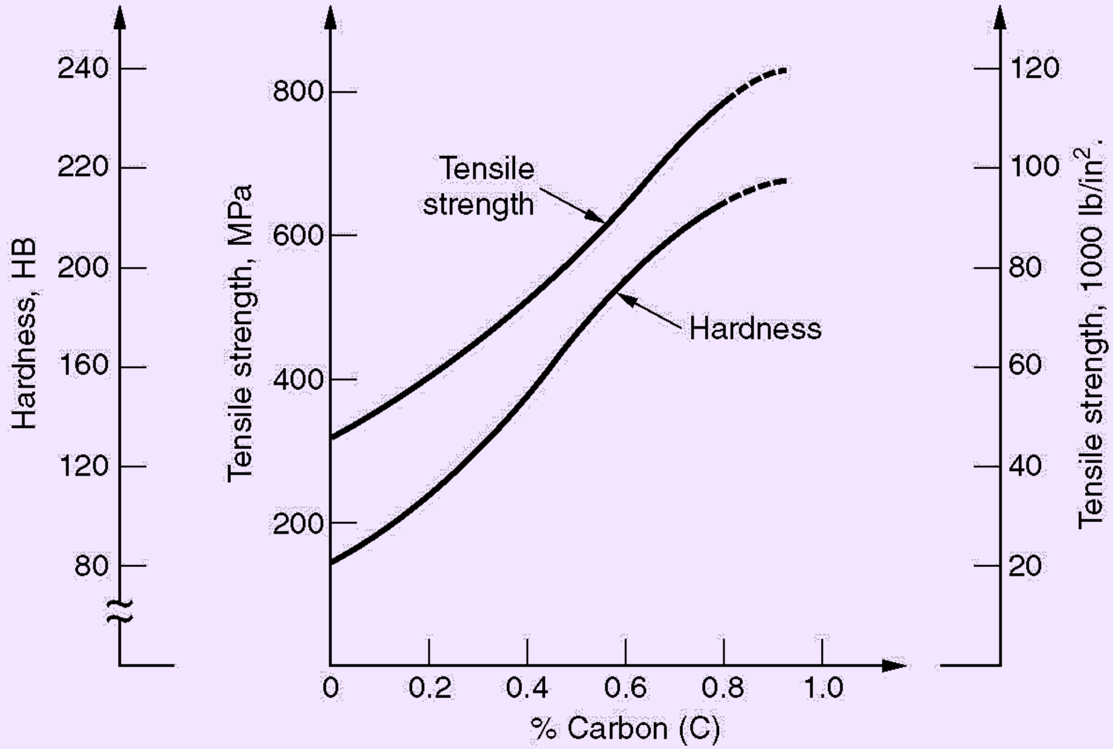
- Carbon is the principal alloying element, with only small amounts of other elements (about 0.5% manganese is normal)

- Strength of plain carbon steels increases with carbon content, but ductility is reduced

Carbon ↗ Strength ↗ Carbon ↗ Ductility ↘

- High carbon steels can be heat treated to form martensite, making the steel very hard and strong

Figure 6.12 Tensile strength and hardness as a function of carbon content in plain carbon steel (hot rolled).



Hardness is the characteristic of a solid material expressing its resistance to permanent deformation. It is expressed as Brinell hardness number or BHN or HB:

P = applied force (kgf)

D = diameter of indenter (mm)

d = diameter of indentation (mm)

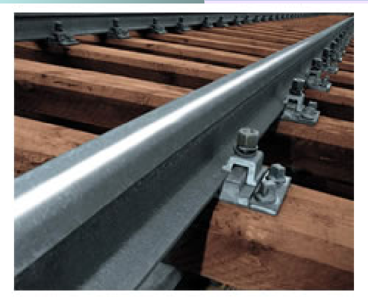
$$\mathrm{BHN} = \frac{2P}{\pi D(D - \sqrt{(D^2 - d^2)})}$$

AISI-SAE Designation Scheme

Specified by a 4-digit number system: 10XX, where 10 indicates plain carbon steel, and XX indicates carbon % in hundredths of percentage points

- For example, 1020 steel contains 0.20% C
- Developed by American Iron and Steel Institute (AISI) and Society of Automotive Engineers (SAE), so designation often expressed as AISI 1020 or SAE 1020

Plain Carbon Steels



1. Low carbon steels - contain less than 0.20% C
   - Applications: automobile sheetmetal parts, plate steel for fabrication, railroad rails

2. Medium carbon steels - range between 0.20% and 0.50% C
   - Applications: machinery components and engine parts such as crankshafts and connecting rods

3. High carbon steels - contain carbon in amounts greater than 0.50%
   - Applications: springs, cutting tools and blades, wear-resistant parts

Low Alloy Steels

Iron-carbon alloys that contain additional alloying elements in amounts totaling less than ~ 5% by weight

Large diameter pipeline

- Mechanical properties superior to plain carbon steels for given applications
- Higher strength, hardness, wear resistance, toughness, and more desirable combinations of these properties
- Heat treatment is often required to achieve these improved properties

AISI-SAE Designation Scheme

AISI-SAE designation uses a 4-digit number system: YYXX, where YY indicates alloying elements, and XX indicates carbon % in hundredths of % points

- Examples:

  13XX - Manganese steel

  20XX - Nickel steel

  31XX - Nickel-chrome steel

  40XX - Molybdenum steel

  41XX - Chrome-molybdenum steel

Stainless Steel (SS)

Highly alloyed steels designed for corrosion resistance

- Principal alloying element is Chromium, usually <u>greater than 15%</u>
  - Cr forms a thin <u>oxide film</u> that protects surface from corrosion

- Nickel (Ni) is another alloying ingredient in certain SS to increase <u>corrosion protection</u>
- Carbon is used to strengthen and harden SS, but high C content reduces corrosion protection since <u>chromium carbide</u> forms to reduce available free Cr

Carbon ↗ Strength ↗ Carbon ↗ Corrosion protection ↘

Properties of Stainless Steels

- In addition to corrosion resistance, stainless steels are noted for their combination of strength and ductility
  - While desirable in many applications, these properties generally make stainless steel difficult to work in manufacturing
- Significantly more expensive than plain C or low alloy steels

3

Types of Stainless Steel

- Classified according to the predominant phase present at ambient temperature:
  1. Austenitic stainless - typical composition 18% Cr and 8% Ni
  2. Ferritic stainless - about 15% to 20% Cr, low C, and no Ni
  3. Martensitic stainless - as much as 18% Cr but no Ni, higher C content than ferritic stainless

Designation Scheme for Stainless Steels

- Three-digit AISI numbering scheme
- First digit indicates general type, and last two digits give specific grade within type
  - Examples:

    Type 302 – Austenitic SS

    18% Cr, 8% Ni, 2% Mn, 0.15% C

    Type 430 – Ferritic SS

    17% Cr, 0% Ni, 1% Mn, 0.12% C

    Type 440 – Martensitic SS

    17% Cr, 0% Ni, 1% Mn, 0.65% C

Additional Stainless Steels

- Stainless steels developed in early 1900s
- Several <u>additional high alloy steels</u> have been developed and are also classified as stainless steels:

4. Precipitation hardening stainless - typical composition = 17% Cr and 7%Ni, with additional small amounts of alloying elements such as Al, Cu, Ti, and Mo (Aerospace applications)
5. Duplex stainless - mixture of austenite and ferrite in roughly equal amounts (heat exchangers, pumps)

Tool Steels

A class of (usually) highly alloyed steels designed for use as industrial cutting tools, dies, and molds

- To perform in these applications, they must possess high strength, hardness, wear resistance, and toughness <u>under impact</u>
- Tool steels are <u>heat treated</u>

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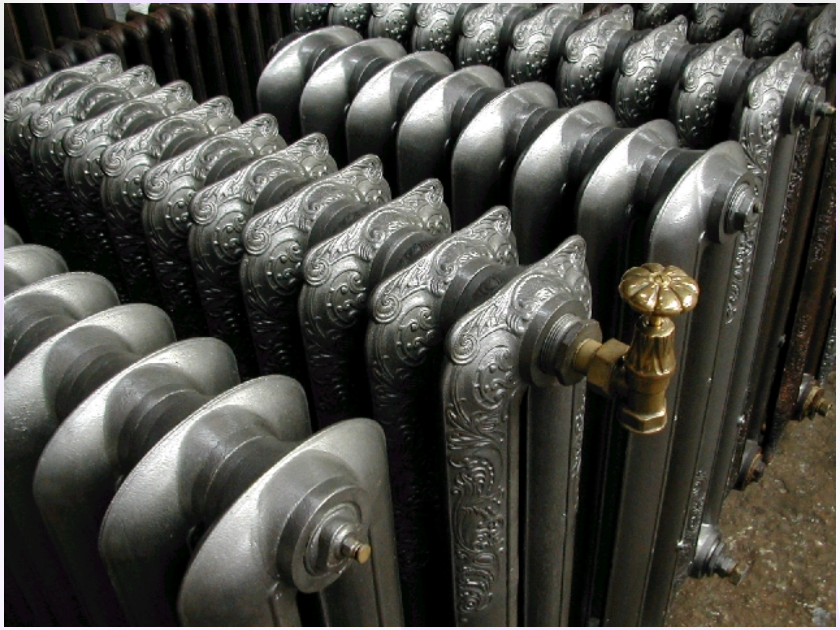
AISI Classification of Tools Steels

T, M	*High-speed tool steels* - cutting tools in machining
H	*Hot-working tool steels* - hot-working dies for forging, extrusion, and die-casting
D	*Cold-work tool steels* - cold working dies for sheetmetal pressworking, cold extrusion, and forging
W	*Water-hardening tool steels* - high carbon but little else
S	*Shock-resistant tool steels* - tools needing high toughness, as in sheetmetal punching and bending
P	*Mold steels* - molds for molding plastics and rubber

Cast Iron



Cast Irons

Iron alloys containing from 2.1% to about 4% carbon and from 1% to 3% silicon

- This composition makes them highly suitable as casting metals
- Tonnage of cast iron castings is several times that of all other cast metal parts combined, excluding cast ingots in steel-making that are subsequently rolled into bars, plates, and similar stock
- Overall tonnage of cast iron is second only to steel among metals

Types of Cast Irons

- Most important is *gray* cast iron

- Other types include *ductile* iron, *white* cast iron, *malleable* iron, and various alloy cast irons

- *Ductile* and *malleable* irons possess chemistries similar to the *gray* and *white* cast irons, respectively, but result from special processing treatments

Gray cast Iron →Special melting and pouring treatment (Chemical treatment) → Ductile Iron
White cast Iron →Heat treatment → Malleable Iron

Topics to be covered

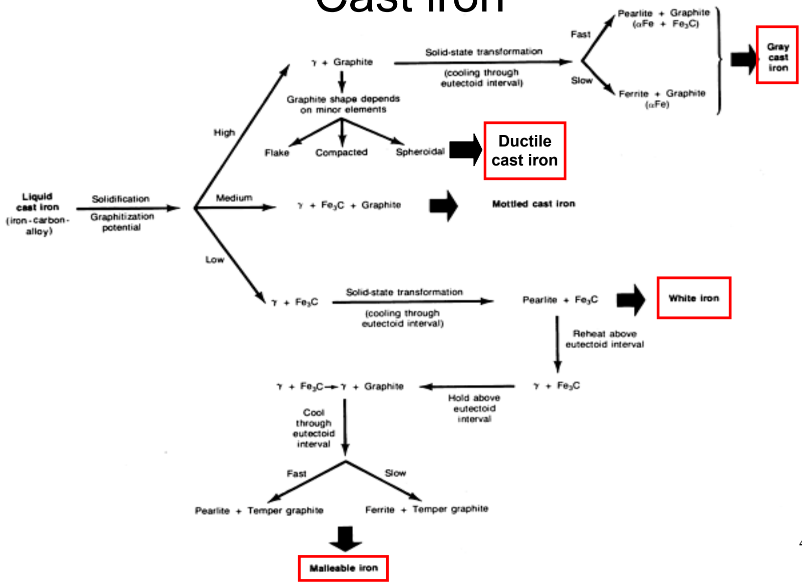
Cast Irons

- Classification
  - White
  - Malleable
  - Gray
  - Ductile
- Applications and advantages of cast irons
- Factors affecting graphitization
- Heat treating to control structure

Cast iron

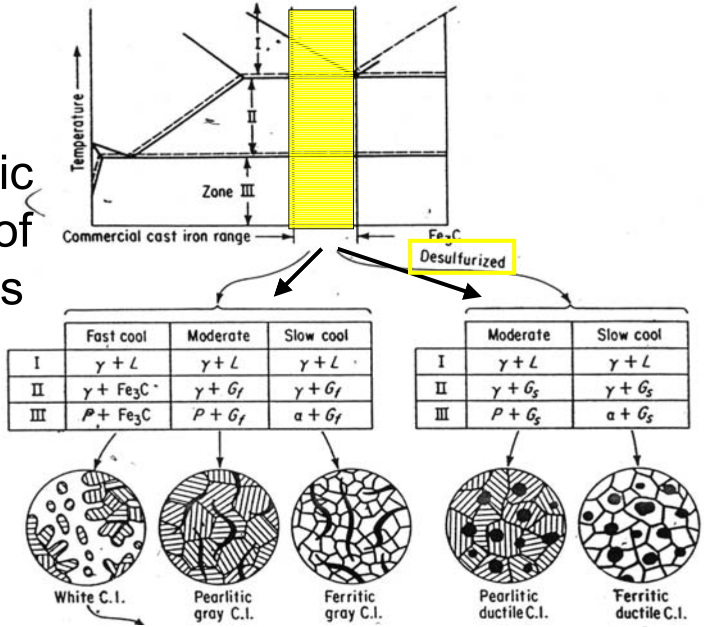
- Family of ferrous alloys
- Cast into desired shape – not worked
- 2-4% C and 1-3% Si
- Instability of Fe_3C:
  - Cementite / graphite flakes / graphite nodules

Cast iron



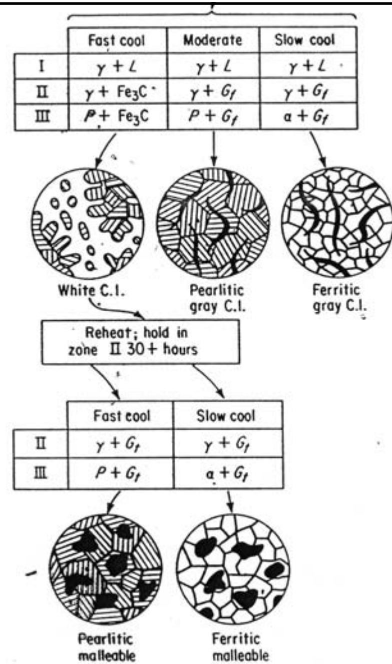
Liquid cast iron
(iron-carbon-alloy)
Solidification
Graphitization potential
High
Medium
Low
γ + Graphite
Solid-state transformation
(cooling through eutectoid interval)
Fast
Slow
Pearlite + Graphite
(αFe + Fe3C)
Ferrite + Graphite
(αFe)
Gray cast iron
Graphite shape depends on minor elements
Flake
Compacted
Spheroidal
Ductile cast iron
γ + Fe3C + Graphite
Mottled cast iron
γ + Fe3C
Solid-state transformation
(cooling through eutectoid interval)
Pearlite + Fe3C
White iron
Reheat above eutectoid interval
γ + Fe3C
Hold above eutectoid interval
γ + Fe3C → γ + Graphite
Cool through eutectoid interval
Fast
Slow
Pearlite + Temper graphite
Ferrite + Temper graphite
Malleable iron

Schematic of types of cast irons



Part 2 of schematic

G_f = flake graphite
G_t = graphite–temper carbon
G_s = graphite spheroids
P = pearlite
α = ferrite
γ = austenite

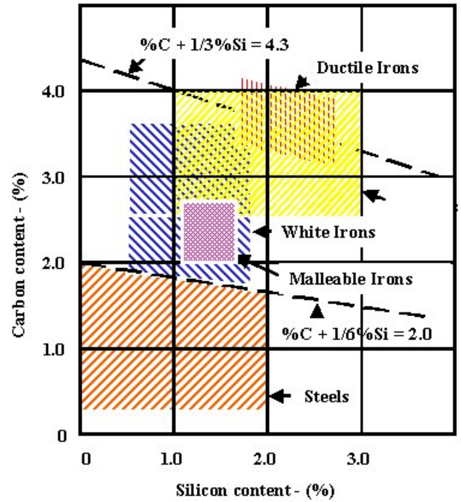


Classification of cast iron

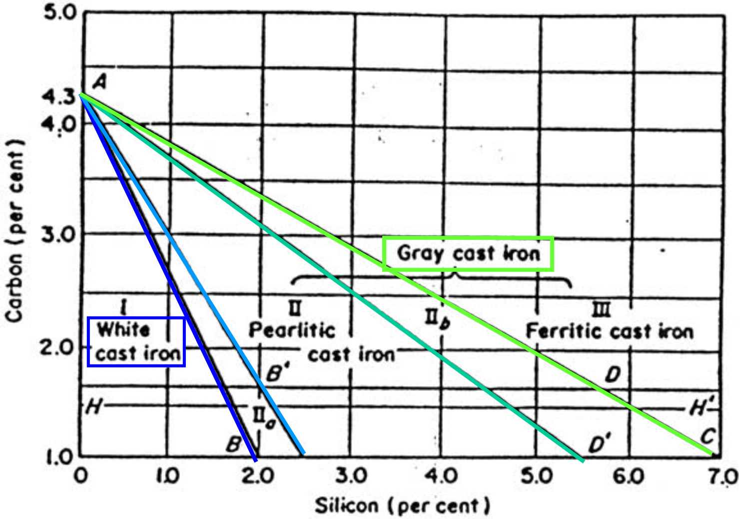
	Type of cast iron	Graphite	Ductility	
•	White	No	No	Fast cooling rates
•	Gray	Flake	No	Slow cooling rates
•	Malleable	**Anneal: flake to nodule**	Yes	white iron + annealing heat treatment
•	Nodular	Nodular	Yes	additions made so that nodules of graphite form instead of flakes

Factors influencing which will form:

- %C
- %Si
- temperature (cooling rate)



Composition and type of cast iron



Cooling rate and type of cast iron

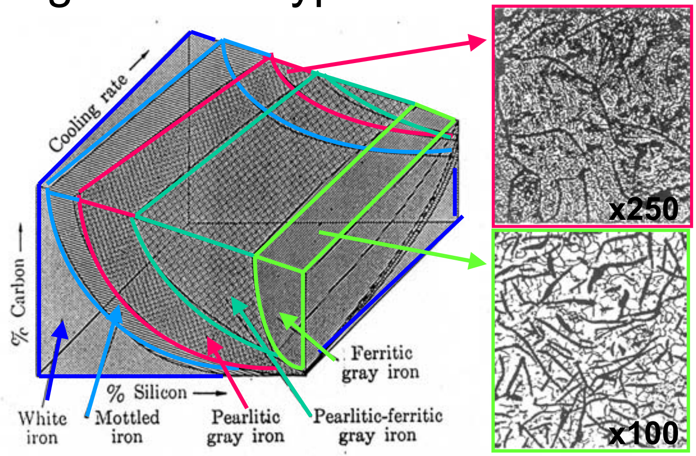
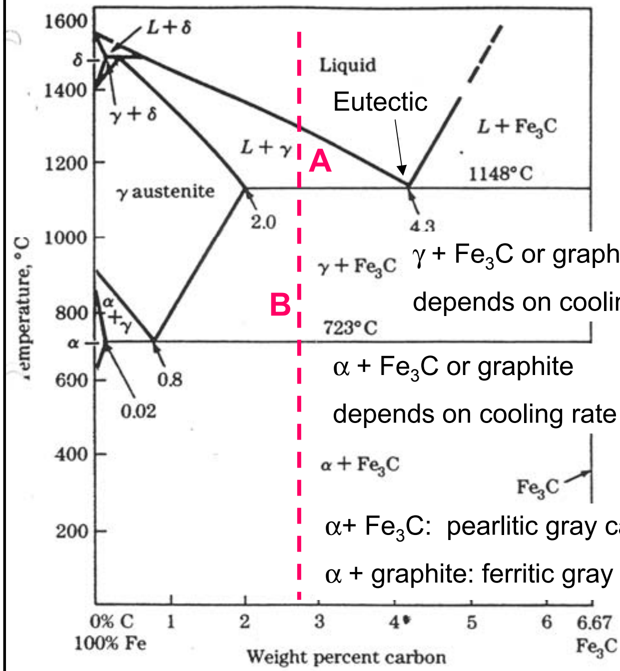


FIG. 5–11. The effect of cooling rate and composition on the structure of cast iron. Mottled cast iron is a mixture of the white and the gray cast iron structures.

On Phase diagram



γ + Fe_3C or graphite depends on cooling rate

α + Fe_3C or graphite depends on cooling rate

α+ Fe_3C: pearlitic gray cast irons or

α + graphite: ferritic gray cast irons

Cast iron: factors affecting graphitization

Metal cools across eutectic T from “A” or from “B” will Fe_3C or graphite form?

γ γ + eutectic liquid at “A”

- fast cooling - γ + Fe_3C (white cast iron)
- slow cooling - γ + graphite (gray cast iron)

γ + graphite (gray cast iron) at point “B”

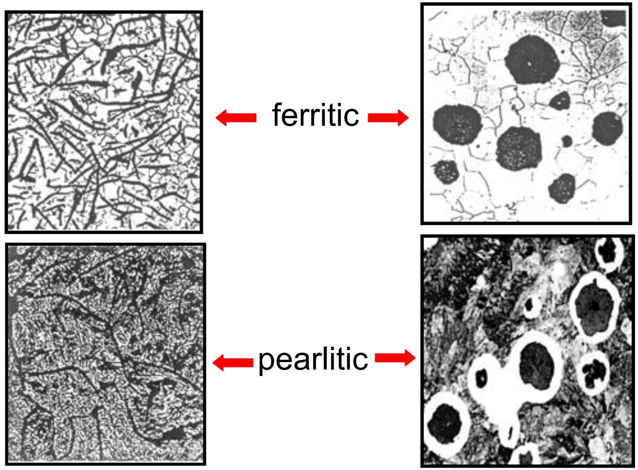
- α + Fe_3C – pearlitic gray cast iron
- α + graphite – ferritic gray cast iron

Cast iron: factors affecting graphitization

Cast iron Carbon Equivalent

- C.E. = %C + 1/3%Si
- Gray and nodular cast iron:
  - higher %C and %Si vs. white and malleable

Grey vs nodular cast iron (x250)



Gray – graphite as flakes

Brittle

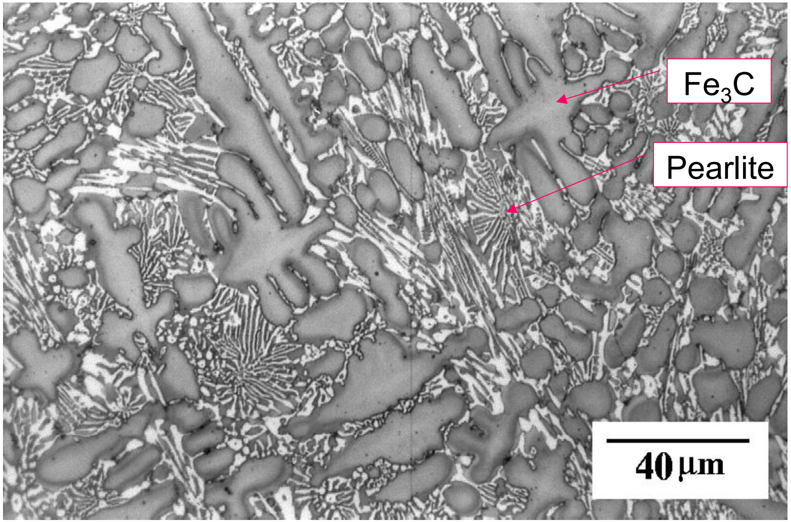
Nodular – graphite as nodules

Ductile

White cast iron

- Fe_3C + pearlite
- Hard, brittle
- Shows a “white” crystalline fractured surface
- Excellent wear resistance
- High compressive stress

White Cast Iron



Malleable cast iron

- White cast iron + annealing treatment
- During annealing treatment graphite nucleates and grows from the Fe_3C to form nodules

Gray cast iron

- During slow solidification carbon in Fe separates or graphitizes to form separate graphite flakes

Ductile/nodular cast iron

- Mg added to molten iron
- Helps to spherodize graphite
- Low levels of minor elements such as

S and P

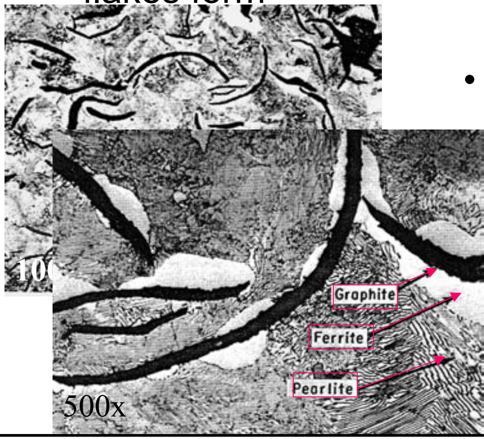
General characteristics/advantages of gray cast iron

- Cheap
- Low melting point
- Fluid – easy to cast, especially advantageous into large complex shapes
- Excellent machinability
- Excellent bearing properties
- Excellent damping properties
- Excellent wear resistance (hi C)
- Can be heat treated (surface hardened etc.)
- Can be alloyed etc.

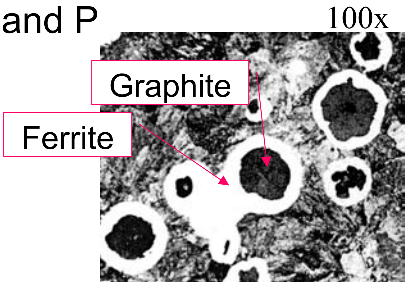
Essentially steel + graphite

Contrasting gray and nodular/ductile cast iron

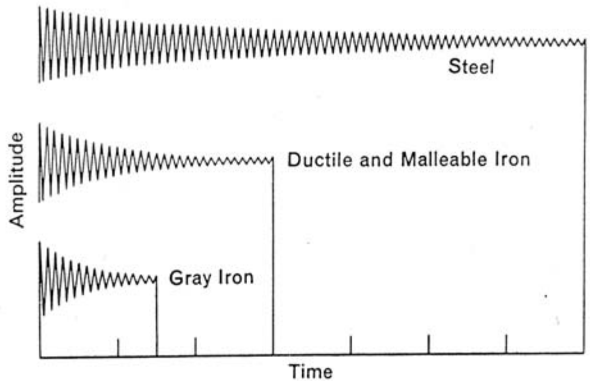
- Separate graphite flakes form



- Mg added to molten iron – helps spherodise graphite
- Low levels of minor elements such as S and P



Great at dampening!



Relative ability of ferrous metals to dampen vibrations. The energy absorbed per cycle, or specific damping capacity of these can differ by more than 10 times.

Gray cast iron (example)

- 3.0 %C
- graphite forms as flakes during solidification
- Have γ dendrites + eutectic γ + graphite flakes at T < 1153°C
- 99% γ + 1 % graphite flakes

Gray cast iron (example)

- at T> eutectoid
- 97.7% γ of eutectoid (0.7%) composition, 2.3% graphite
- If cooling fast –pearlite (pearlitic gray cast iron)
- If cooling slow – ferritic gray cast iron

- May have a mixture of ferrite and pearlite:
  - Ferrite regions around flakes, rest pearlite
  - Class 20+60 Y.S. – 134 MPa; UTS – 402 MPa

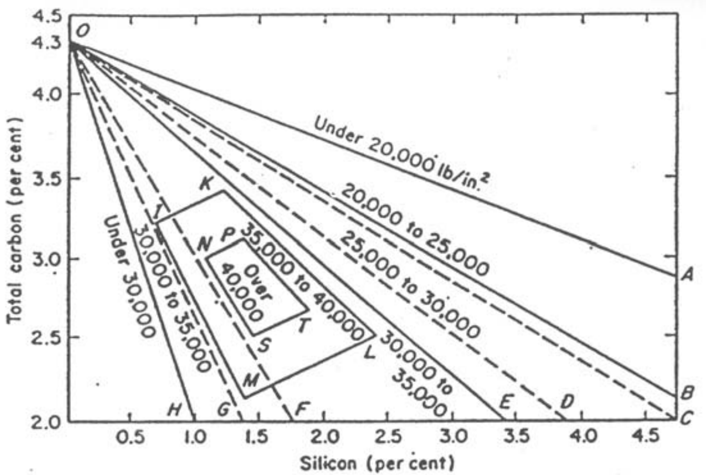
Gray cast iron

- γ + graphite on cooling to eutectoid T (723^oC) must decide:
  - $\gamma \Rightarrow \alpha$ + graphite
  - $\gamma \Rightarrow \alpha$ +pearlite
- Favoured by slow cooling rates, starts as a) but as diffusion path increases, difficult to maintain, therefore reverts to $\alpha + Fe_3C$

Comments on tensile properties

- Ferritic – softest; pearlitic – strongest
- Variation in elastic modulus
- 0 ductility – tensile strengths only quoted
  - C – 2.75-3.5%, Si 1.5-3.0%
  - Graphite flake types and size
- Fine uniform size wanted, get by:
  - increased superheat to casting
  - Inoculation with ferrosilicon or calcium silicon

Tensile properties



Applications of ductile cast irons

TABLE 8-3
Common grades and typical applications of ductile cast irons

Type TS-YS-% elongation	Tensile strength, psi	Yield strength, psi	Typical elonga-tion, %	Hardness, Bhn	Heat treatment	Typical microstructure	Typical applications
60-40-18	60,000	40,000	18	137–170	Annealed	All ferritic	Pressure castings such as valve and pump bodies.
65-45-12	65,000	45,000	12	149–229	—	Ferritic	Machinery castings subject to shock and fatigue loading
80-55-06	80,000	55,000	6	179–255	—	Ferritic and pearlitic	Crankshaft gears and rollers
100-70-03	100,000	70,000	3	229–302	Normalized	All Pearlitic	High strength gears, automotive and machine components
120-90-02	120,000	90,000	2	250–350^{+}	Quench and temper	Tempered martensitic	Pinions, gears, rollers and slides

Ductile/nodular cast iron

- Gray iron composition for C and Si
- Impurity level control important as it will affect nodule formation
- Have nodule instead of flake if we add in 0.05% Mg and/or Ce
- As cast structure: graphite forms as nodules instead of flakes

Heat treatment control

- If we want more ductility (less strength) heat treat to convert pearlitic areas to α + graphite
  - Heat to 900°C
  - Cool at 20˚C/hr from 790° to 650°CF
  - Normal furnace cooling
  - Could be done as one step with slower original cooling

Nodular cast iron

- γ + graphite on cooling below A_1 must decide:
  - $\gamma \Rightarrow \alpha$ + graphite
  - $\gamma \Rightarrow \alpha + Fe_3C$
- Favoured by slow cooling rates, short diffusion paths etc.

γ first follows a) in regions surrounding nodules.
Carbon diffuses to existing nodules.
As T decreases and diffusion path increases remaining
$\gamma \Rightarrow \alpha + Fe_3C$(pearlite)

Heat treatment control

- If we want more ductility (less strength) heat treat to convert pearlitic areas to α + graphite
  - Heat to 900°C
  - Cool at 20˚C/hr from 790° to 650°CF
  - Normal furnace cooling
  - Could be done as one step with slower original cooling