



METALS

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



Four Types of Engineering Materials

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



Metals: The Most Important Engineering Materials

- They have properties that satisfy a wide variety of design requirements
- The manufacturing processes by which they are shaped into products have been developed and refined over many years
- Engineers understand 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

- Some metals are important as pure elements (e.g., gold, silver, copper)
- Most engineering applications require the enhanced properties obtained by alloying
- Through alloying, it is possible to increase strength, hardness, and other properties compared to pure metals



Alloys

An *alloy* = a mixture or compound of two or more elements, at least one of which is metallic

- Two main categories:
 1. Solid solutions
 2. Intermediate phases



Solid Solutions

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

- A *phase* = any homogeneous mass of material, such as a metal in which the grains all have the same crystal lattice structure
- In a solid solution, the solvent or base element is metallic, and the dissolved element can be either metallic or nonmetal



Two Forms of Solid Solutions

1. Substitutional solid solution - atoms of solvent element are replaced in its unit cell by dissolved element
2. 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

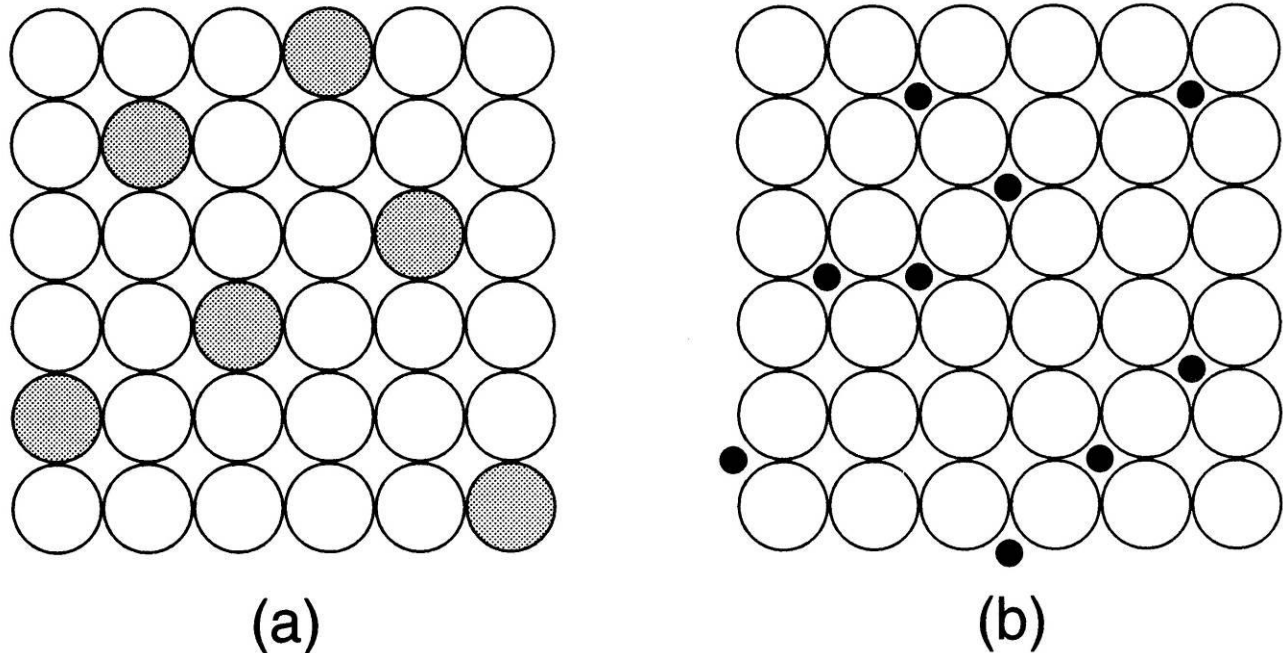


Figure 6.1 Two forms of solid solutions: (a) substitutional solid solution, and (b) interstitial solid solution.



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

A graphical means of representing 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*
 - Other forms of phase diagrams are discussed in texts on metallurgy and materials science



Phase Diagrams

- 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 Phase Diagram

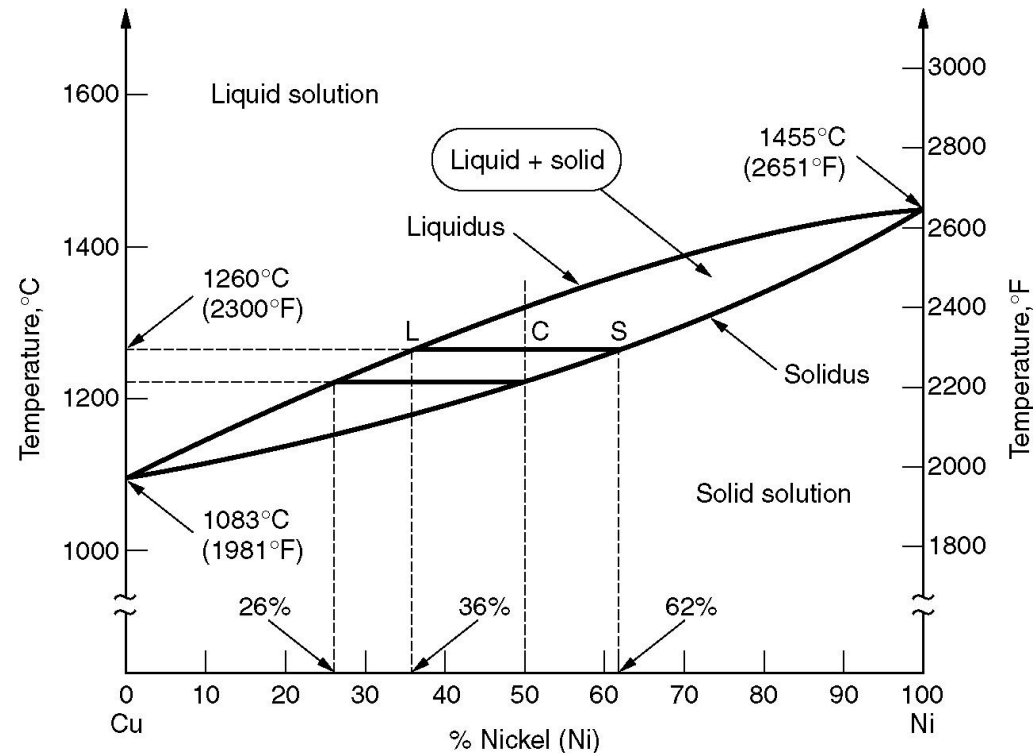


Figure 6.2 Phase diagram for the copper-nickel alloy system.



Copper-Nickel (Cu-Ni) Alloy System

- Solid solution alloy throughout entire range of compositions below the solidus
- No intermediate solid phases in this alloy system
- However, there is a mixture of phases (solid + liquid) in the region bounded by the solidus and liquidus

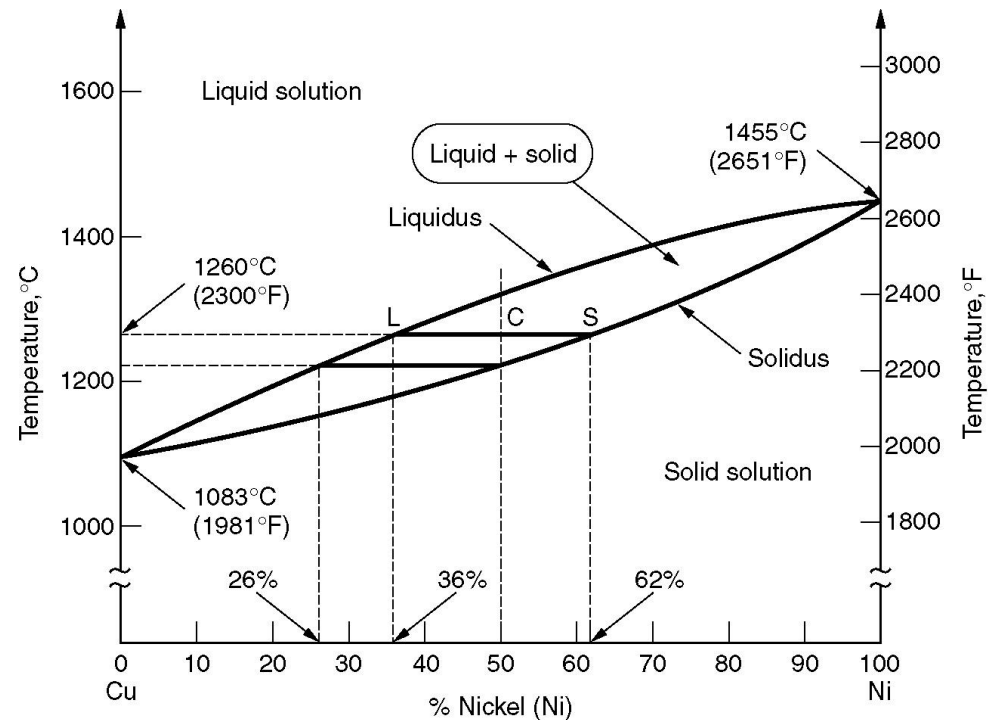


Chemical Compositions of Phases

- 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

Example

Determine compositions of liquid and solid phases in the Cu-Ni system at an aggregate composition of 50% nickel and a temperature of 1316°C (2400°F)





Inverse Lever Rule – Step 1

- The phase diagram can be used to determine the amounts of each phase present at a given temperature
 - Using the horizontal line that indicates overall composition at a given temperature, measure the distances between the aggregate composition and the intersection points with the liquidus and solidus, identifying the distances as CL and CS, respectively



Inverse Lever Rule – Step 2

- The proportion of liquid phase present is given by

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

- And the proportion of solid phase present is given by

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



Applications of the Inverse Lever Rule

- Methods for determining chemical composition of phases and amounts of each phase are applicable to the solid region of the phase diagram as well as the liquidus-solidus region
- Wherever there are regions in which two phases are present, these methods can be utilized
- When only one phase is present, the composition of the phase is its aggregate composition under equilibrium conditions, and the inverse lever rule does not apply

Tin-Lead Phase Diagram

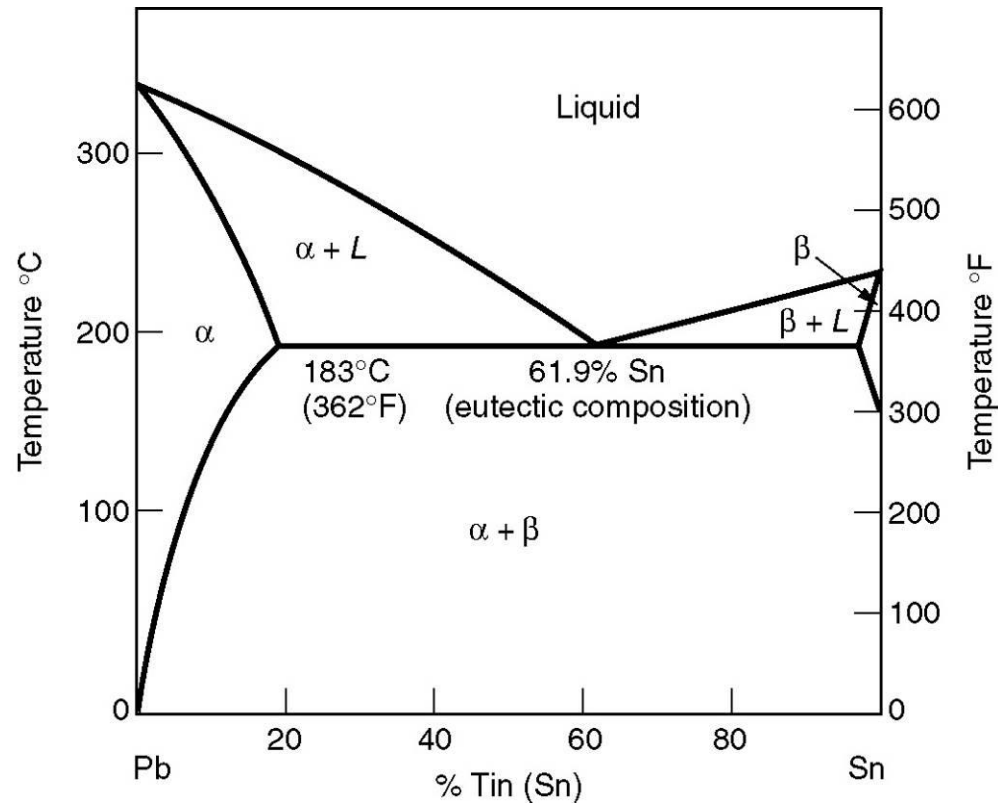


Figure 6.3 Phase diagram for the tin-lead alloy system.



Tin-Lead (Sn-Pb) Alloy System

- Widely used in soldering for making electrical connections
- Sn-Pb system includes two solid phases, alpha (α) and beta (β)
 - α -phase = solid solution of tin in lead at left side of diagram
 - β -phase = solid solution of lead in tin at around 200°C (375°F) at right side of diagram
- Between these solid solutions lies a mixture of the two solid phases, $\alpha + \beta$



Melting in the Tin-Lead Alloy System

- Pure tin melts at 232°C (449°F)
- Pure lead melts at 327°C (621°F)
- Tin-lead alloys melt at lower temperatures
- The diagram shows two liquidus lines that begin at the melting points of the pure metals and meet at a composition of 61.9% Sn
 - This is the *eutectic composition* for the tin-lead system



Eutectic Alloy

A particular composition in an alloy system for which the solidus and liquidus are at the same temperature

- The *eutectic temperature* = melting point of the eutectic composition
 - The eutectic temperature is always the lowest melting point for an alloy system
- The word *eutectic* is derived from the Greek word *eutektos*, meaning easily melted



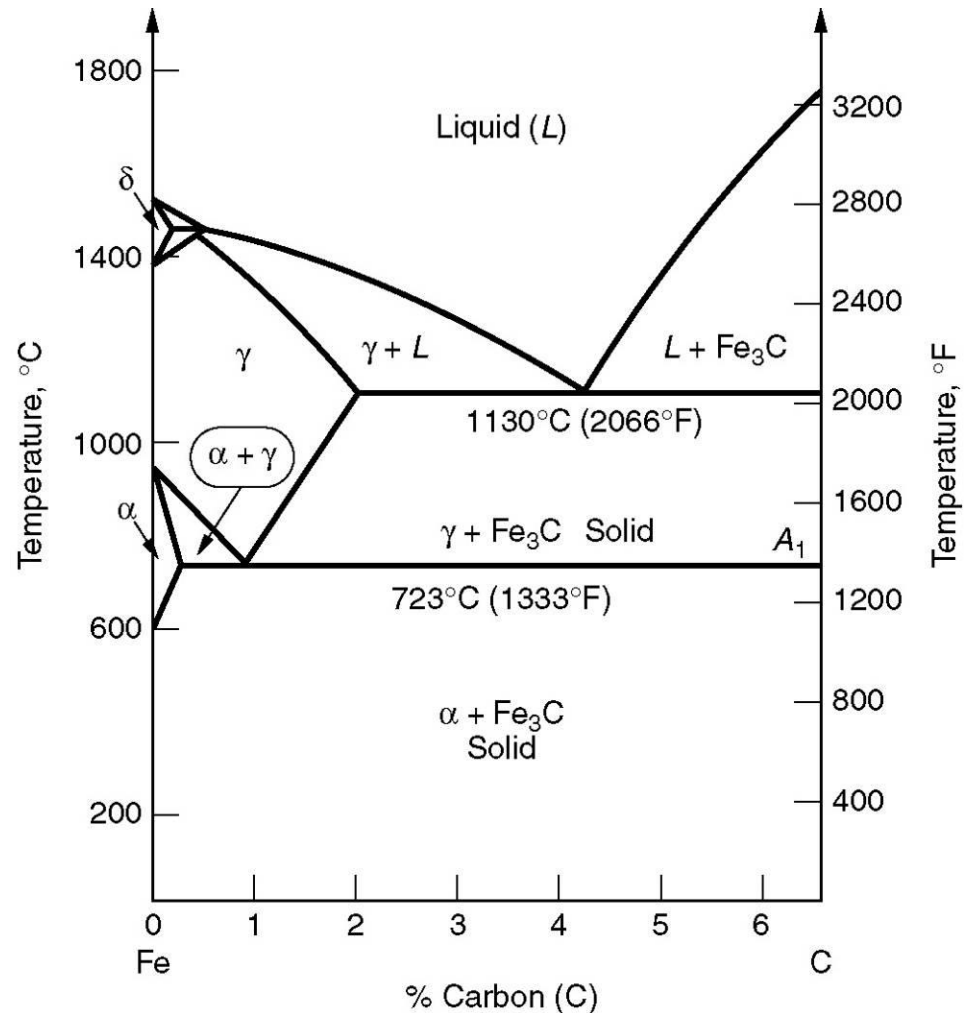
Ferrous Metals

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

Iron-Carbon Phase Diagram

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





The Several Phases of Iron

- The phase at room temperature is alpha (α), called *ferrite* (BCC)
- At 912°C (1674°F), ferrite transforms to gamma (γ), called *austenite* (FCC)
- This transforms at 1394°C (2541°F) to delta (δ) (BCC)
- Pure iron melts at 1539°C (2802°F)



Iron as a Commercial Product

- Electrolytic iron - the most pure, at about 99.99%, for research and other purposes where the pure metal is required
- Ingot iron - contains about 0.1% impurities (including about 0.01% carbon), used in applications where high ductility or corrosion resistance are needed
- Wrought iron - contains about 3% slag but very little carbon, and is easily shaped in hot forming operations such as forging



Solubility Limits of Carbon in Iron

- Ferrite phase can dissolve only about 0.022% carbon at 723°C (1333°F)
- Austenite can dissolve up to about 2.1% carbon at 1130°C (2066°F)
 - The difference in solubility between alpha and gamma provides opportunities for strengthening by heat treatment



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



Cementite in the Iron-Carbon System

- At room temperature under equilibrium conditions, iron-carbon alloys form a two-phase system at carbon levels even slightly above zero
- The second phase is Fe_3C , also known as cementite

Cementite = an intermediate phase: a metallic compound of iron and carbon that is hard and brittle



Eutectic and Eutectoid Compositions

Eutectic composition of Fe-C system = 4.3% C

- Phase changes from solid ($\gamma + \text{Fe}_3\text{C}$) to liquid at 1130°C (2066°F)

Eutectoid composition of Fe-C system = 0.77% C

- Phase changes from α to γ above 723°C (1333°F)
- Below 0.77% C, called *hypoeutectoid steels*
- From 0.77 to 2.1% C, called *hypereutectoid steels*



Iron and Steel Production

- Iron making - iron is reduced from its ores
- Steel making – iron is then refined to obtain desired purity and composition (alloying)



Iron Ores Required in Iron-making

- The principal ore used in the production of iron and steel is *hematite* (Fe_2O_3)
- Other iron ores include *magnetite* (Fe_3O_4), *siderite* (FeCO_3), and *limonite* ($\text{Fe}_2\text{O}_3 \cdot x\text{H}_2\text{O}$, where x is typically around 1.5)
- Iron ores contain from 50% to around 70% iron, depending on grade (hematite is almost 70% iron)
- Scrap iron and steel are also widely used today as raw materials in iron- and steel making



Other Raw Materials in Iron-making

- Coke (C)
 - Supplies heat for chemical reactions and produces carbon monoxide (CO) to reduce iron ore
- Limestone (CaCO_3)
 - Used as a flux to react with and remove impurities in molten iron as slag
- Hot gases (CO , H_2 , CO_2 , H_2O , N_2 , O_2 , and fuels)
 - Used to burn coke



Iron-making in a Blast Furnace

Blast furnace - a refractory-lined chamber with a diameter of about 9 to 11 m (30 to 35 ft) at its widest and a height of 40 m (125 ft)

- To produce iron, a charge of ore, coke, and limestone are dropped into the top of a blast furnace
- Hot gases are forced into the lower part of the chamber at high rates to accomplish combustion and reduction of the iron

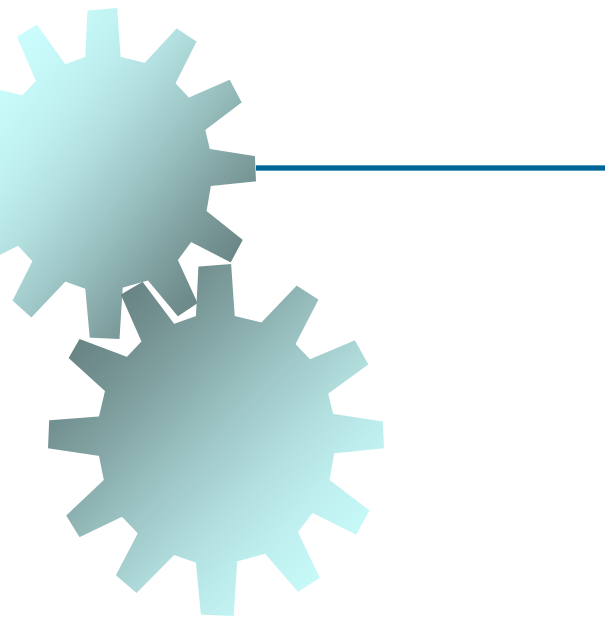
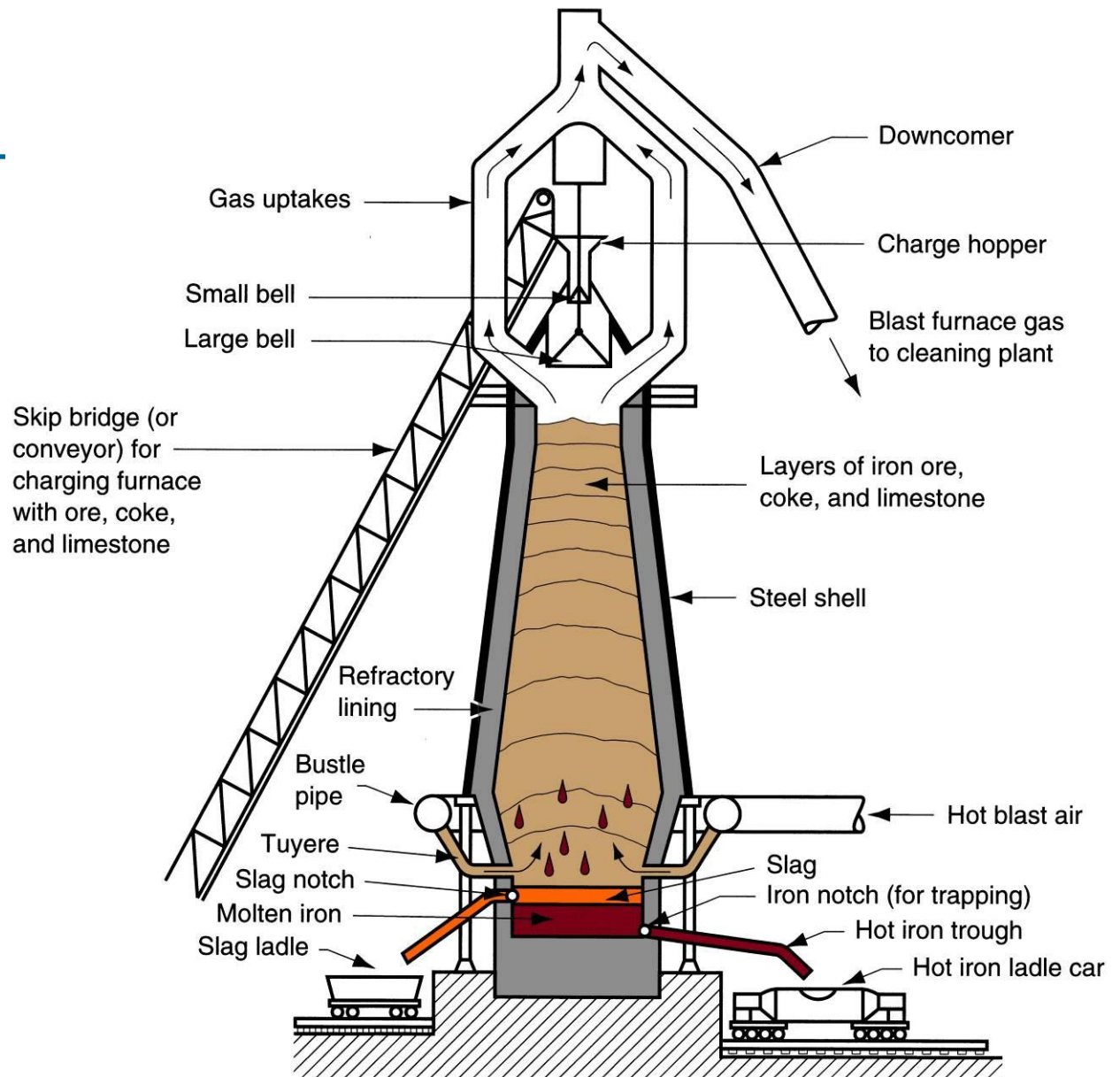


Figure 6.5
Cross-section of
iron-making
blast furnace
showing major
components





Chemical Reactions in Iron-Making

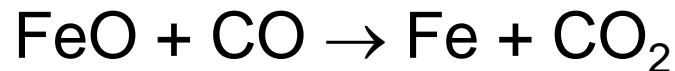
- Using hematite as the starting ore:



- CO_2 reacts with coke to form more CO:



- This accomplishes final reduction of FeO to iron:





Proportions of Raw Materials In Iron-Making

- Approximately seven tons of raw materials are required to produce one ton of iron:
 - 2.0 tons of iron ore
 - 1.0 ton of coke
 - 0.5 ton of limestone
 - 3.5 tons of gases
- A significant proportion of the byproducts are recycled



Iron from the Blast Furnace

- Iron tapped from the blast furnace (called *pig iron*) contains over 4% C, plus other impurities: 0.3-1.3% Si, 0.5-2.0% Mn, 0.1-1.0% P, and 0.02-0.08% S
- Further refinement is required for cast iron and steel
 - A furnace called a *cupola* is commonly used for converting pig iron into gray cast iron
 - For steel, compositions must be more closely controlled and impurities brought to much lower levels



Steel-making

- Since the mid-1800s, a number of processes have been developed for refining pig iron into steel
- Today, the two most important processes are
 - Basic oxygen furnace (BOF)
 - Electric furnace
- Both are used to produce carbon and alloy steels



Basic Oxygen Furnace (BOF)

- Accounts for ~ 70% of steel production in U.S
- Adaptation of the Bessemer converter
 - Bessemer process used air blown up through the molten pig iron to burn off impurities
 - BOF uses pure oxygen
- Typical BOF vessel is ~ 5 m (16 ft) inside diameter and can process 150 to 200 tons per heat
 - Cycle time (tap-to-tap time) takes ~ 45 min

Basic Oxygen Furnace

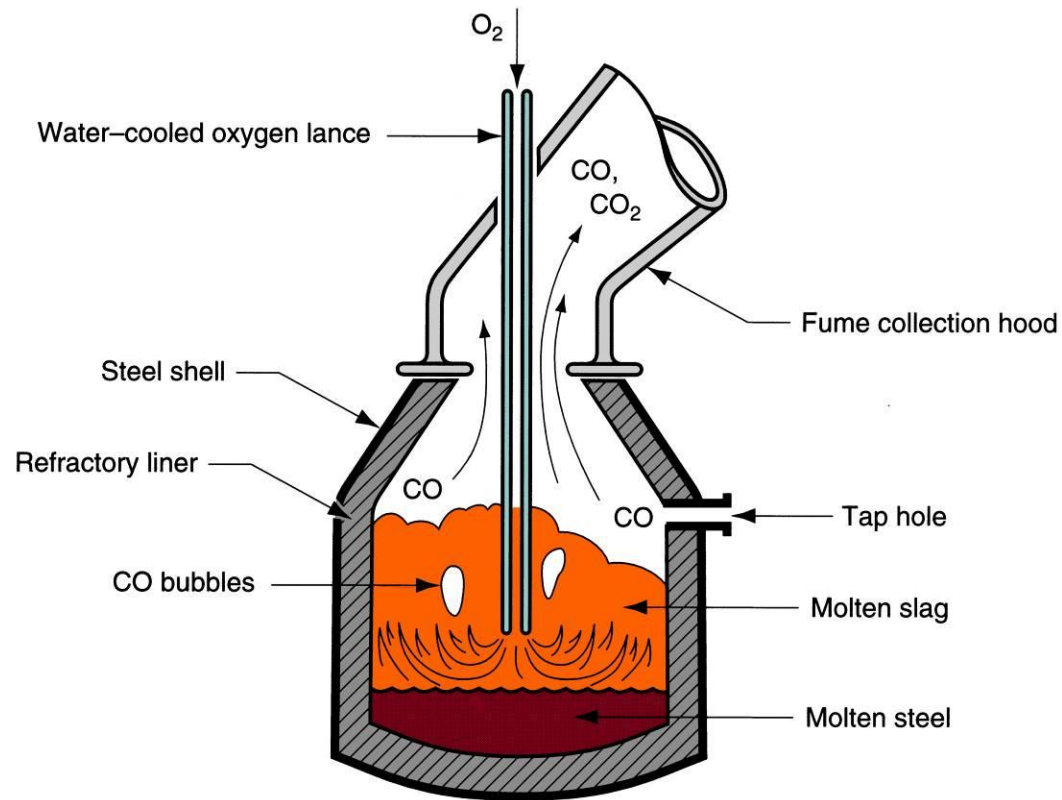


Figure 6.7 Basic oxygen furnace showing BOF vessel during processing of a heat.

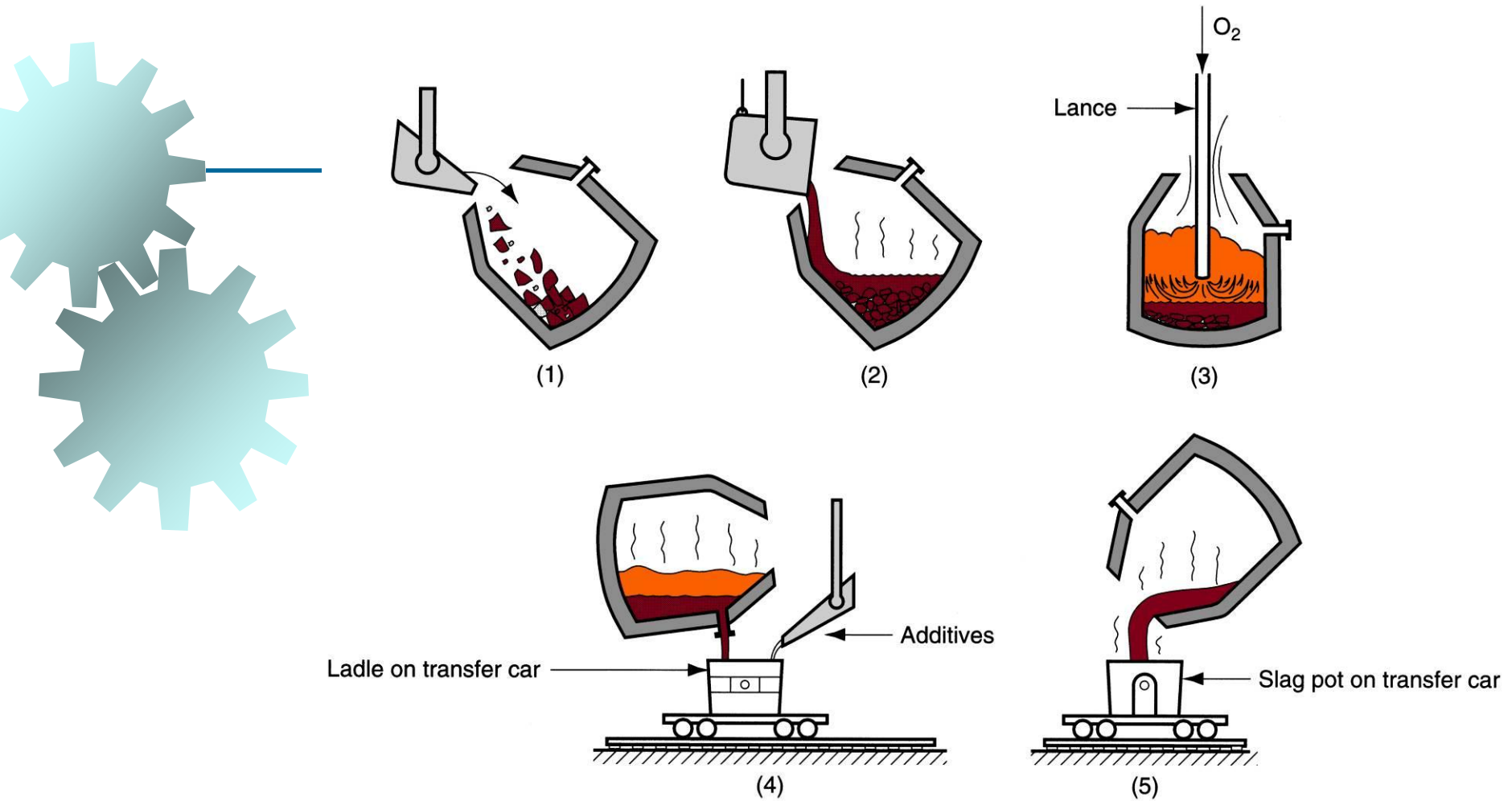


Figure 6.8 BOF sequence : (1) charging of scrap and (2) pig iron, (3) blowing, (4) tapping the molten steel, (5) pouring off the slag.





Electric Arc Furnace

- Accounts for ~ 30% of steel production in U.S.
- Scrap iron and scrap steel are primary raw materials
- Capacities commonly range between 25 and 100 tons per heat
- Complete melting requires about 2 hr; tap-to-tap time is 4 hr
- Usually associated with production of alloy steels, tool steels, and stainless steels
- Noted for better quality steel but higher cost per ton, compared to BOF

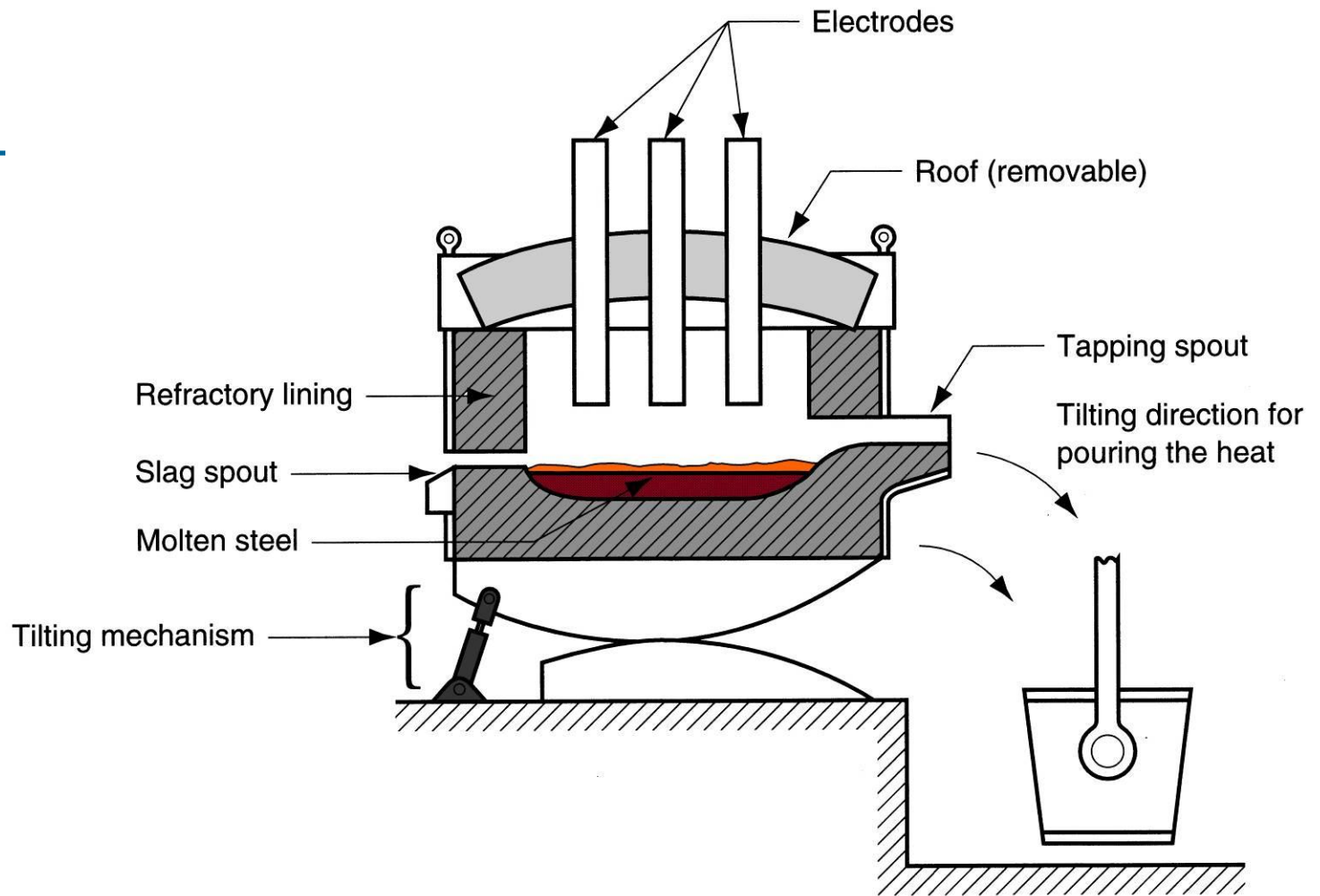


Figure 6.9 Electric arc furnace for steelmaking.



Casting Processes in Steel-making

- Steels produced by BOF or electric furnace are solidified for subsequent processing either as cast ingots or by continuous casting
 - Casting of ingots – a discrete production process
 - Continuous casting – a semi-continuous process



Casting of Ingots

Steel *ingots* = discrete castings weighing from less than one ton up to ~ 300 tons (entire heat)

- Molds made of high carbon iron, tapered at top or bottom for removal of solid casting
- The mold is placed on a platform called a *stool*
 - After solidification the mold is lifted, leaving the casting on the stool

Ingot Mold

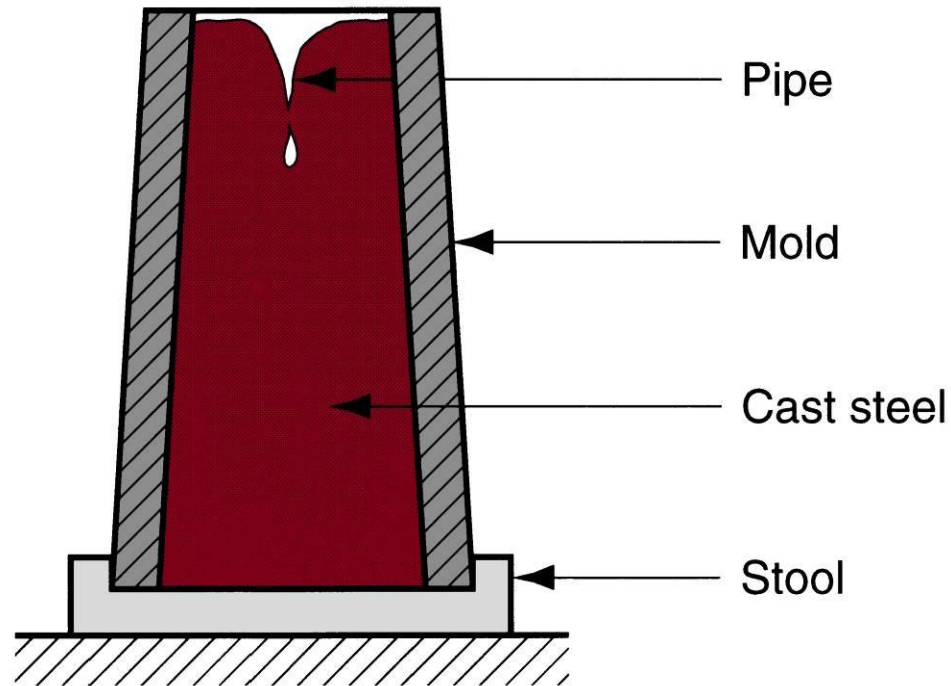


Figure 6.10 A big-end-down ingot mold typical of type used in steelmaking.



Continuous Casting

- Continuous casting is widely applied in aluminum and copper production, but its most noteworthy application is steel-making
- Dramatic productivity increases over ingot casting, which is a discrete process
- For ingot casting, 10-12 hr may be required for casting to solidify
 - Continuous casting reduces solidification time by an order of magnitude

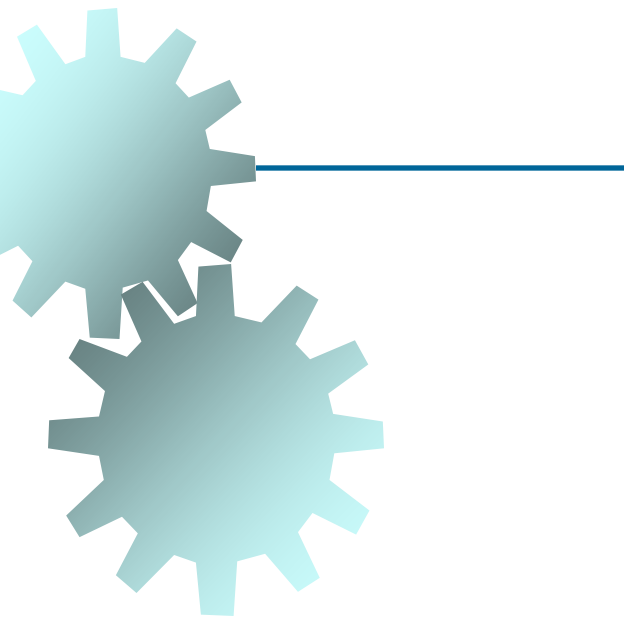
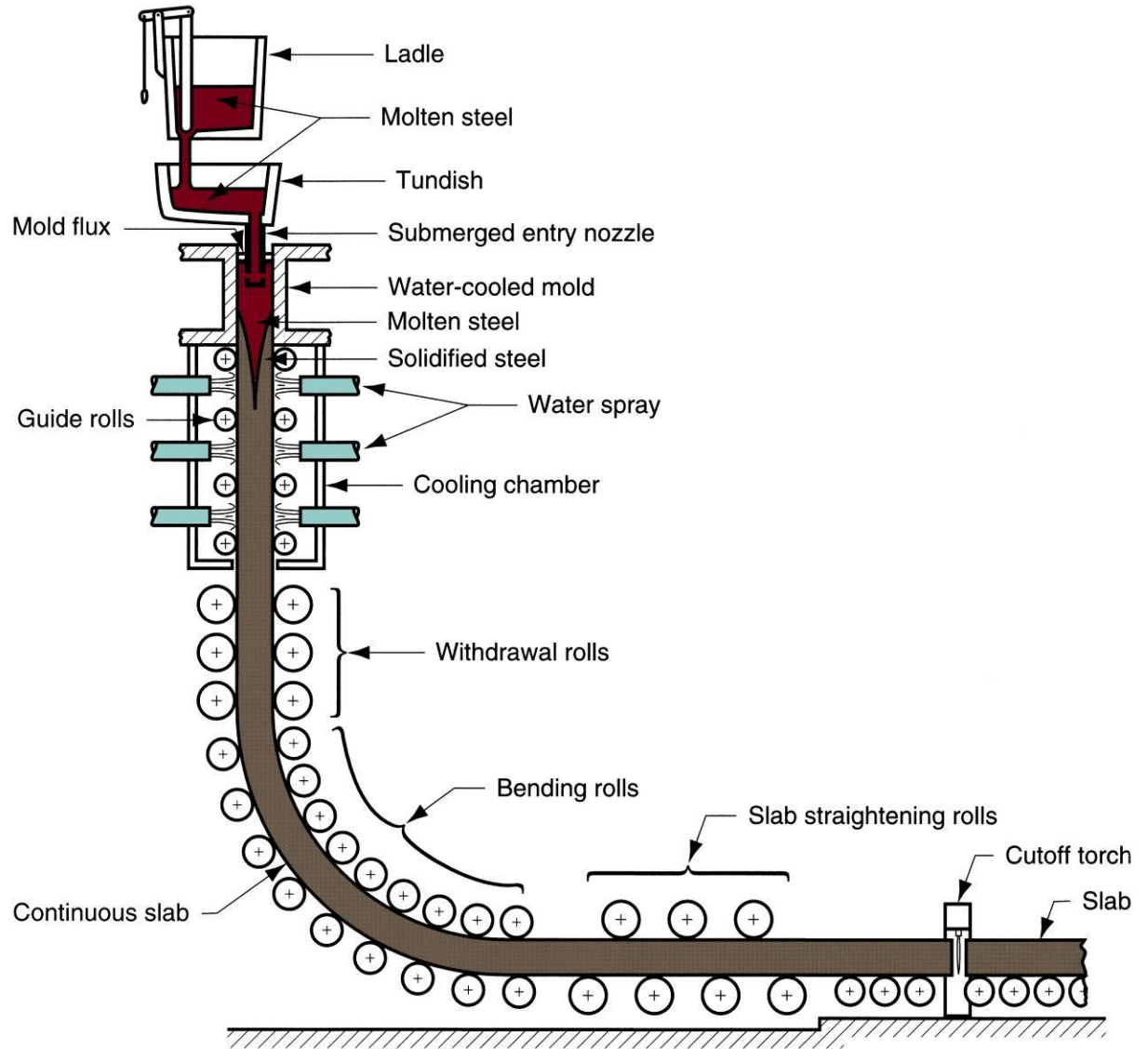


Figure 6.11 Continuous casting. Steel is poured into tundish and flows into a water-cooled continuous mold; it solidifies as it travels down in mold. Slab thickness is exaggerated for clarity.





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

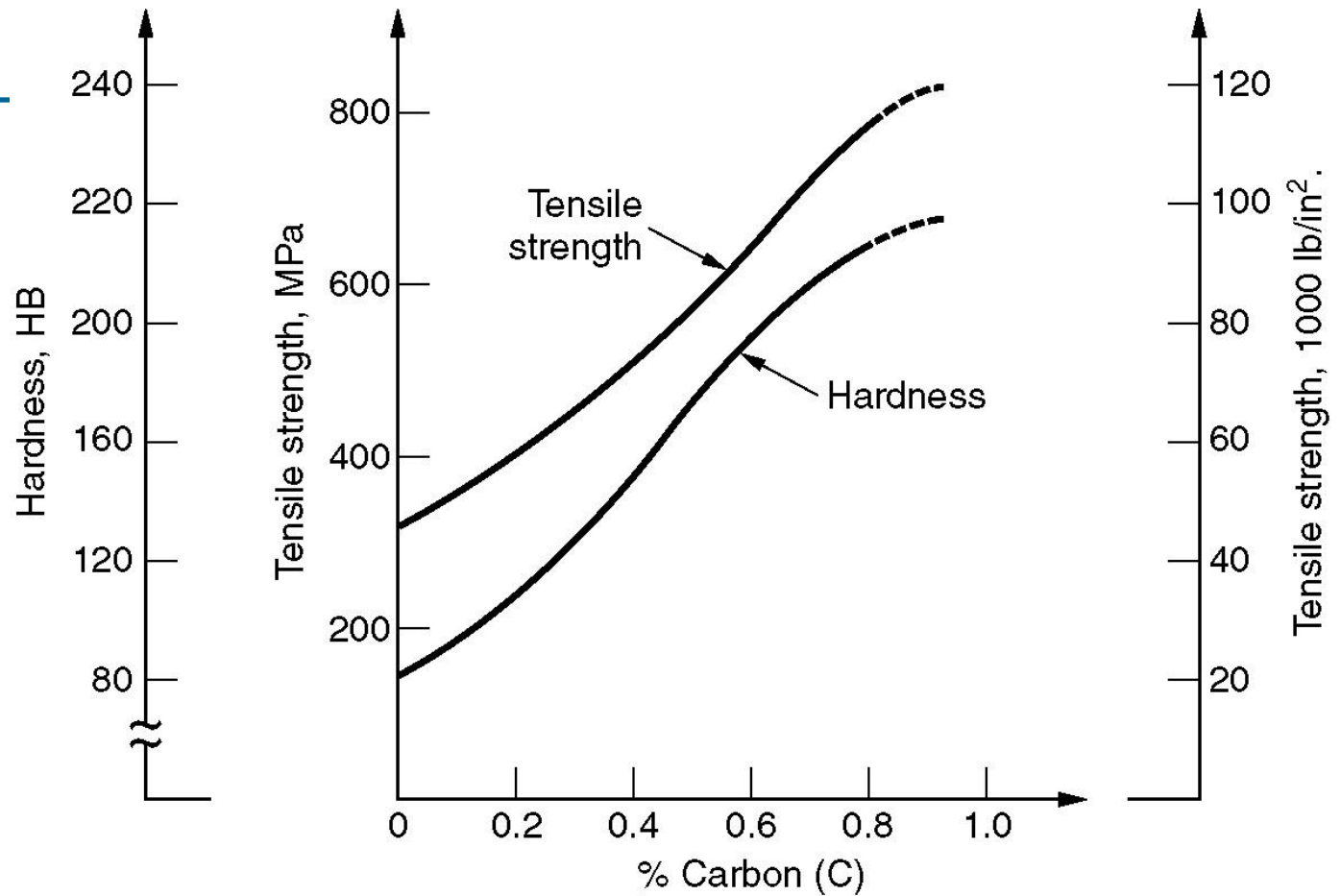
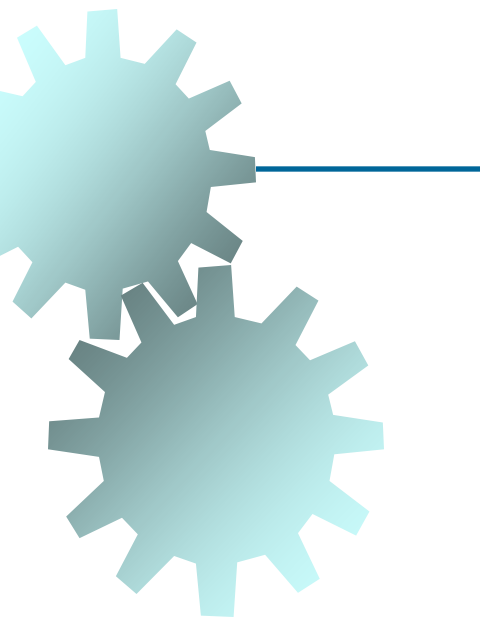


Figure 6.12 Tensile strength and hardness as a function of carbon content in plain carbon steel (hot rolled).



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 $\sim 5\%$ by weight

- Mechanical properties superior to plain carbon steels for given applications
- Higher strength, hardness, hot 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 greater than 15%
 - Cr forms a thin impervious oxide film that protects surface from corrosion
- Nickel (Ni) is another alloying ingredient in certain SS to increase corrosion protection
- Carbon is used to strengthen and harden SS, but high C content reduces corrosion protection since chromium carbide forms to reduce available free Cr



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



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 additional high alloy steels 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
 5. Duplex stainless - mixture of austenite and ferrite in roughly equal amounts



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, hot hardness, wear resistance, and toughness under impact
- Tool steels are heat treated



AISI Classification of Tools Steels

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



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

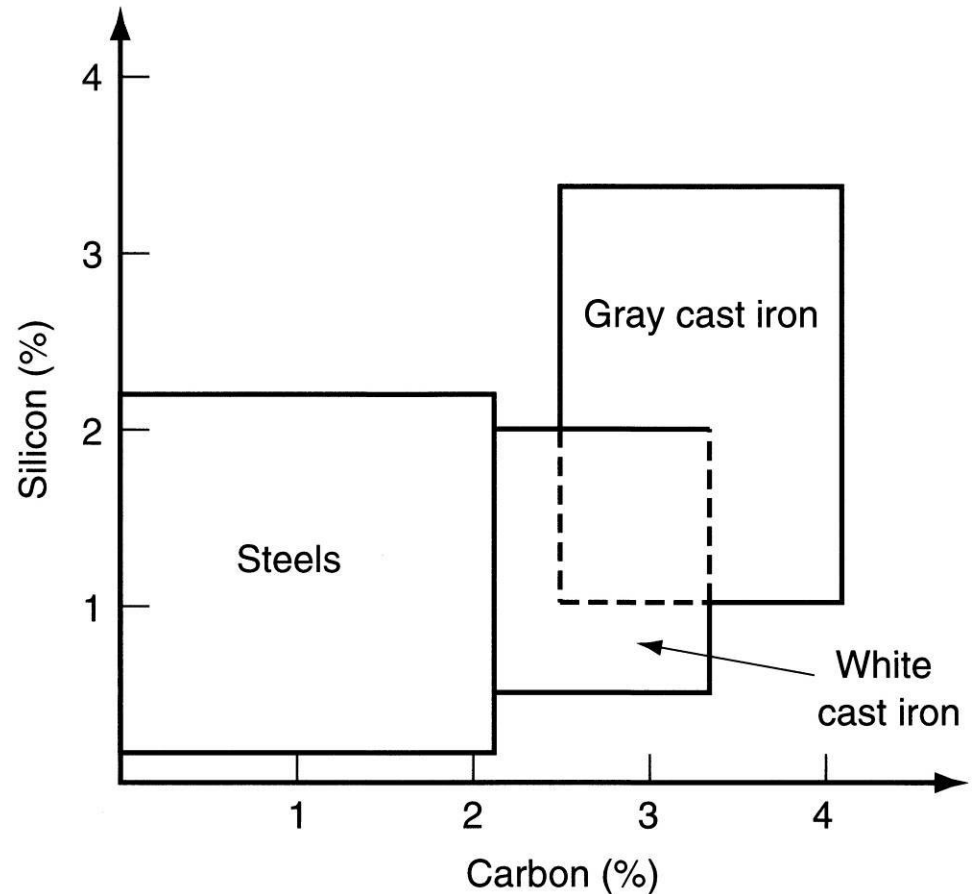
- Most important is *gray* cast iron
- Other types include *ductile* iron, *white* cast iron, *malleable* iron, and various alloy cast irons
- *Ductile* and *malleable* irons possess chemistries similar to the *gray* and *white* cast irons, respectively, but result from special processing treatments

Cast Iron Chemistries

Figure 6.13 Carbon and silicon % for cast irons, compared to steels (most steels have relatively low Si % - cast steels have higher Si %).

Ductile iron is formed by special melting and pouring treatment of gray cast iron.

Malleable iron is formed by heat treatment of white cast iron.





Nonferrous Metals

Metal elements and alloys not based on iron

- Most important nonferrous metals are aluminum, copper, magnesium, nickel, titanium, and zinc, and their alloys
- Although not as strong as steels, certain nonferrous alloys have corrosion resistance and/or strength-to-weight ratios that make them competitive with steels in moderate to high stress applications
- Many nonferrous metals have properties other than mechanical that make them ideal for applications in which steel would not be suitable



Aluminum and Magnesium

- Aluminum (Al) and magnesium (Mg) are light metals
 - They are often specified in engineering applications for this feature
- Both elements are abundant on earth, aluminum on land and magnesium in the sea
 - Neither is easily extracted from their natural states



Aluminum Production

- Principal ore is *bauxite* - mostly hydrated aluminum oxide ($\text{Al}_2\text{O}_3\text{-H}_2\text{O}$) + other oxides
- Extraction of Al from bauxite consists of:
 - Washing and crushing the ore into fine powders
 - *Bayer process* – conversion of bauxite into pure alumina (Al_2O_3)
 - *Electrolysis* – separation of alumina into aluminum and oxygen gas (O_2)



Properties of Aluminum

- High electrical and thermal conductivity
- Excellent corrosion resistance due to formation of a hard thin oxide surface film
- Very ductile metal, noted for its formability
- Pure aluminum is relatively low in strength, but it can be alloyed and heat treated to compete with some steels, especially when weight is taken into consideration



Designation Scheme for Aluminum

Four-digit code number to identify composition

- Two designations to distinguish wrought aluminums from cast aluminums
 - Difference is that a decimal point follows the third digit for cast aluminums, no decimal point for wrought product



Designations of Wrought and Cast Aluminum Alloys (Partial List)

<u>Alloy group</u>	<u>Wrought code</u>	<u>Cast code</u>
Aluminum \geq 99.0% purity	1XXX	1XX.X
Copper alloy	2XXX	2XX.X
Manganese alloy	3XXX	
Silicon alloy	4XXX	4XX.X
Zinc alloy	7XXX	7XX.X
Tin alloy		8XX.X



Designation Scheme for Aluminum

- Properties of Al alloys are influenced by work hardening and heat treatment, so temper must be designated in addition to composition
 - This designation is attached to the 4-digit code, separated by a hyphen, to indicate treatment or no treatment
 - Temper treatments that specify strain hardening do not apply to the cast alloys



Temper Designations for Aluminum Alloys (Partial List)

<u>Temper</u>	<u>Description</u>
F	As fabricated - no special treatment
H	Strain hardened (wrought aluminums)
O	Annealed to relieve strain hardening and improve ductility
T	Thermal treatment to produce stable tempers other than F, H, or O



Magnesium and Its Alloys

- Lightest of the structural metals
- Available in both wrought and cast forms
- Relatively easy to machine
- In all processing of magnesium, small particles of the metal (such as small metal cutting chips) oxidize rapidly, and care must be taken to avoid fire hazards



Magnesium Production

- Sea water contains about 0.13% MgCl_2
 - This is the source of most commercially produced magnesium
- To extract Mg, sea water is mixed with milk of lime - calcium hydroxide (Ca(OH)_2)
- Resulting reaction precipitates magnesium hydroxide (Mg(OH)_2) that settles and is removed as a slurry
- Slurry is then filtered to increase (Mg(OH)_2) content



Magnesium Production - continued

- Slurry is mixed with hydrochloric acid (HCl), which reacts with the hydroxide to form concentrated MgCl_2 - much more concentrated than the original sea water
- Electrolysis is used to decompose salt into magnesium (Mg) and chlorine gas (Cl_2)
 - Magnesium is then cast into ingots for subsequent processing
 - Chlorine is recycled to form more MgCl_2



Properties of Magnesium

- As a pure metal, magnesium is relative soft and lacks sufficient strength for most engineering applications
- However, it can be alloyed and heat treated to achieve strengths comparable to aluminum alloys
- In particular, its strength-to-weight ratio is an advantage in aircraft and missile components



Designation Scheme for Magnesium

Three-to-five character alphanumeric code

- First two characters = letters that identify principal alloying elements (up to two elements)
- Followed by a two-digit number that indicates, respectively, the amounts of the two alloying ingredients to nearest percent
 - Example: AZ63A – aluminum 6%, zinc 3%, magnesium 93%



Designation Scheme for Magnesium

- Last symbol is a letter that indicates variation in composition or simply chronological order in which alloy became commercially availability
- Magnesium alloys also require specification of a temper, and the same basic scheme for aluminum is used for magnesium alloys



Copper

- One of the oldest metals known to mankind
- Low electrical resistivity - commercially pure copper is widely used as an electrical conductor
- Also an excellent thermal conductor
- One of the *noble metals* (gold and silver are also noble metals), so it is corrosion resistant



Copper Production

- In ancient times, copper was available in nature as a free element
- Today, copper is extracted from ores such as *chalcopyrite* (CuFeS_2)
- Ore is crushed, concentrated by flotation, and then *smelted* (melted or fused, often with a chemical reaction to separate the metal from its ore)
 - Resulting copper is 98% to 99% pure
 - Electrolysis is used to obtain higher purity levels for commercial use



Copper Alloys

- Strength and hardness of copper is relatively low; to improve strength, copper is frequently alloyed
- Bronze - alloy of copper and tin (typical ~ 90% Cu, 10% Sn), widely used today and in ancient times (i.e., the *Bronze Age*)
- Brass - alloy of copper and zinc (typical ~ 65% Cu, 35% Zn).
- Highest strength alloy is beryllium-copper (only about 2% Be), which can be heat treated to high strengths and used for springs



Designation Scheme for Copper

Based on the Unified Numbering System for Metals and Alloys (UNS), using a five digit number preceded by the letter C (for copper)

- Includes both wrought and cast copper and their alloys

- Examples:

C10100 – 99.99% pure copper

C17000 – 98% Cu, 1.7% Be (beryllium-copper)

C24000 – 80% Cu, 20% Zn (brass)

C52100 – 92% Cu, 8% Sn (bronze)



Nickel and Its Alloys

- Similar to iron in some respects:
 - Magnetic
 - Modulus of elasticity $\cong E$ for iron and steel
- Differences with iron:
 - Much more corrosion resistant - widely used as (1) an alloying element in steel, e.g., stainless steel, and (2) as a plating metal on metals such as plain carbon steel
 - High temperature properties of Ni alloys are superior



Nickel Production

- To extract nickel from its ore, *pentlandite* ($(\text{Ni,Fe})_9\text{S}_8$), the ore is crushed and ground with water
- Flotation is used to separate sulfides from other minerals in the ore
- Nickel sulfide is then heated to burn off sulfur, followed by *smelting* to remove iron and silicon
- Further refinement is done to yield high-concentration nickel sulfide (NiS)
- Electrolysis is then used to recover high-purity nickel from NiS



Nickel Alloys

- Alloys of nickel are commercially important and are noted for corrosion resistance and high temperature performance
- In addition, a number of superalloys are based on nickel
- Applications: stainless steel alloying ingredient, plating metal for steel, applications requiring high temperature and corrosion resistance



Titanium and Its Alloys

- Abundant in nature, constituting $\sim 1\%$ of earth's crust (aluminum is $\sim 8\%$)
- Density of Ti is between aluminum and iron
- Importance has grown in recent decades due to its aerospace applications where its light weight and good strength-to-weight ratio are exploited



Titanium Production

- Principal ores are *rutile* (98%-99% TiO_2) and *ilmenite* (combination of FeO and TiO_2)
- To recover Ti from its ores, TiO_2 is converted to titanium tetrachloride (TiCl_4) by reacting with chlorine gas
- TiCl_4 is then reduced to metallic titanium by reaction with magnesium, known as the *Kroll process*
 - Resulting metal is used to cast ingots of titanium and its alloys



Properties of Titanium

- Coefficient of thermal expansion is relatively low among metals
- Stiffer and stronger than Al
- Retains good strength at elevated temperatures
- Pure Ti is reactive, which presents problems in processing, especially in molten state
- At room temperature Ti forms a thin adherent oxide coating (TiO_2) that provides excellent corrosion resistance



Applications of Titanium

- In the commercially pure state, Ti is used for corrosion resistant components, such as marine components and prosthetic implants
- Titanium alloys are used as high strength components at temperatures ranging up to above 550°C (1000°F), especially where its excellent strength-to-weight ratio is exploited
 - Examples: aircraft and missile components
- Alloying elements used with titanium include aluminum, manganese, tin, and vanadium



Zinc and Its Alloys

- Low melting point makes it attractive as a casting metal, especially die casting
- Also provides corrosion protection when coated onto steel or iron
 - The term *galvanized steel* refers to steel coated with zinc
- Widely used as alloy with copper (*brass*)



Production of Zinc

- Principal ore is *zinc blende* or *sphalerite* (ZnS)
- Due to small % of ZnS in the ore, sphalerite must be concentrated by first crushing, then grinding with water to create a slurry
- The slurry is agitated so mineral particles float to the top and are skimmed off
- The concentrated ZnS is then roasted, so zinc oxide (ZnO) is formed from reaction
- Zn is then liberated from ZnO by electrolysis or thermochemical reactions



Lead and Tin

- Often considered together due to their low melting points and use in soldering alloys
- Lead - dense, low melting point; low strength, low hardness, high ductility, good corrosion resistance
 - Applications: solder, bearings, ammunition, type metals, x-ray shielding, storage batteries, and vibration damping
- Tin - lower melting point than lead; low strength, low hardness, good ductility
 - Applications: solder, *bronze*, "tin cans" for storing food



Refractory Metals

- Metals capable of enduring high temperatures - maintaining high strength and hardness at elevated temperatures
- Most important refractory metals:
 - Molybdenum
 - Tungsten
- Other refractory metals:
 - Columbium
 - Tantalum



Molybdenum

- Properties: high melting point, stiff, strong, good high temperature strength
- Used as a pure metal (99.9+% Mo) and alloyed
- Applications: heat shields, heating elements, electrodes for resistance welding, dies for high temperature work (e.g., die casting molds), and parts for rocket and jet engines
- Also widely used as an alloying ingredient in steels (e.g., high speed steel) and superalloys



Tungsten

- Properties: highest melting point among metals, one of the densest, also the stiffest (highest modulus of elasticity) and hardest of all pure metals
- Applications typically characterized by high operating temperatures: filament wire in incandescent light bulbs, parts for rocket and jet engines, and electrodes for arc welding
- Also widely used as an element in tool steels, heat resistant alloys, and tungsten carbide



Precious Metals

- Gold, platinum, and silver
 - Called *noble metals* because chemically inert
 - Available in limited supplies
- Used throughout civilized history for coinage and to underwrite paper currency
- Widely used in jewelry and similar applications that exploit their high value
- Properties: high density, good ductility, high electrical conductivity and corrosion resistance, and moderate melting temperatures



Superalloys

High-performance alloys designed to meet demanding requirements for strength and resistance to surface degradation at high service temperatures

- Many superalloys contain substantial amounts of three or more metals, rather than consisting of one base metal plus alloying elements
- Commercially important because they are very expensive
- Technologically important because of their unique properties



Why Superalloys are Important

- Room temperature strength properties are good but not outstanding
- High temperature performance is excellent - tensile strength, hot hardness, creep resistance, and corrosion resistance at very elevated temperatures
- Operating temperatures often around 1100°C (2000°F)
- Applications: gas turbines - jet and rocket engines, steam turbines, and nuclear power plants (all are systems in which operating efficiency increases with higher temperatures)



Three Groups of Superalloys

1. Iron-based alloys - in some cases iron is less than 50% of total composition
 - Alloyed with Ni, Cr, Co
2. Nickel-based alloys - better high temperature strength than alloy steels
 - Alloyed with Cr, Co, Fe, Mo, Ti
3. Cobalt-based alloys - ~ 40% Co and ~ 20% chromium
 - Alloyed with Ni, Mo, and W
- In virtually all superalloys, including iron based, strengthening is by precipitation hardening



Manufacturing Processes for Metals

- Metals are shaped by all of the basic shaping processes: casting, powder metallurgy, deformation, and material removal
- In addition, metal parts are joined to form assemblies by welding, brazing, soldering, and mechanical fastening
- Heat treating is used to enhance properties
- Finishing processes (e.g., electroplating and painting) are commonly used to improve appearance of metal parts and/or to provide corrosion protection



How to Enhance Mechanical Properties

- Alloying - to increase strength of metals
- Cold working - strain hardening during deformation to increase strength (also reduces ductility)
 - Strengthening of the metal occurs as a byproduct of the forming operation
- Heat treatment - heating and cooling cycles performed on a metal to beneficially change its mechanical properties
 - Operate by altering the microstructure of the metal, which in turn determines properties