Chapter 11: Metal Alloys Applications and Processing

ISSUES TO ADDRESS...

• How are metal alloys classified and how are they used?
• What are some of the common fabrication techniques?
• How do properties vary throughout a piece of material that has been quenched, for example?
• How can properties be modified by post heat treatment?
Metals and Metal Alloys

• Includes steels, aluminum, magnesium, zinc, cast iron, titanium, copper and nickel.
• An alloy is a metal that contains additions of one or more metals or non-metals in relatively small amounts.
• Have metallic bonding

Properties:
• Good conductors of heat and electricity
• High strength
• High stiffness
• High ductility
• High density
• Not transparent to visible light
• Resistance to fracture
Chapter 11 -

Alloying, heat treatment and hardening

Metal alloys

Ferrous

Steels

Low alloy

Low-carbon

Plain

High strength, low alloy

Medium-carbon

Plain

Heat treatable

High-carbon

Plain

Tool

Stainless

Cast irons

Gray iron

Ductile (nodular) iron

White iron

Malleable iron

Compacted graphite iron
Taxonomy of Metals

Metal Alloys

Adapted from Fig. 11.1, Callister 7e.

(Fig. 11.1 adapted from Binary Alloy Phase Diagrams, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)
Iron is the prime constituent

Ferrous alloys are used extensively because:

- Iron containing compounds exist in **abundant** quantities within the earth’s crust

- Metallic iron and steel alloys may be produced using relatively **economical** extraction, refining, alloying and fabrication techniques

- Ferrous alloys are extremely **versatile**, have a wide range of mechanical and physical properties
Iron is the prime constituent

Limitations of ferrous alloys include

- Relatively **high densities**
- Comparatively **low electrical conductivities**
- Susceptible to **corrosion** in common environments
Chapter 11 - Ferrous Alloys

The most common types are:

- Cast irons
- Steels
- Ferroalloys
# Steels

## Classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Carbon Content</th>
<th>Uses</th>
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</thead>
<tbody>
<tr>
<td>Low Alloy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low carbon</td>
<td>&lt;0.25 wt% C</td>
<td>auto, struc., bridges, press., vessels</td>
</tr>
<tr>
<td>Med carbon</td>
<td>0.25-0.6 wt% C</td>
<td>crank shafts, bolts, hammers, blades</td>
</tr>
<tr>
<td>High carbon</td>
<td>0.6-1.4 wt% C</td>
<td>pistons, gears, wear, applic., drills, saws, dies</td>
</tr>
<tr>
<td>High Alloy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Low Alloy</th>
<th>Med Alloy</th>
<th>High Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>plain</td>
<td>HSLA</td>
<td>plain</td>
</tr>
<tr>
<td>Additions</td>
<td>none</td>
<td>Cr, V, Ni, Mo</td>
<td>none</td>
</tr>
<tr>
<td>Example</td>
<td>1010</td>
<td>4310</td>
<td>1040</td>
</tr>
<tr>
<td>Hardenability</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>TS</td>
<td>-</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>EL</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Uses</td>
<td>auto</td>
<td>bridges</td>
<td>crank</td>
</tr>
<tr>
<td></td>
<td>struc.</td>
<td>towers</td>
<td>shafts</td>
</tr>
<tr>
<td></td>
<td>sheet</td>
<td>press.</td>
<td>bolts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vessels</td>
<td>blades</td>
</tr>
</tbody>
</table>

Increasing strength, cost, decreasing ductility

Based on data provided in Tables 11.1(b), 11.2(b), 11.3, and 11.4, Callister 7e.
Refinement of Steel from Ore

Iron Ore + Coke + Limestone → Molten iron + slag

CO\(_2\) + C → 2CO
3CO + Fe\(_2\)O\(_3\) → 2Fe + 3CO\(_2\)
CaCO\(_3\) → CaO + CO\(_2\)
CaO + SiO\(_2\) + Al\(_2\)O\(_3\) → slag
Iron carbon alloys that may contain some other elements

Mechanical properties are sensitive to carbon content

Carbon content is normally less than 1.0 wt%
Low-Carbon Steels

- Produced in the greatest quantities
- Contain less than about 0.25 wt%
- Microstructures contains pearlite and ferrite
- Relatively soft and weak
- Outstanding ductility and toughness
- Machinable and weldable
- Least expensive to produce
Low-Carbon Steels

- Least expensive to produce
- Automobile body components
- Sheets that are used in pipelines, buildings, bridges and tin cans
Medium-Carbon Steels

• Carbon concentrations between about 0.25 and 0.60 wt%

• Low hardenabilities

• Stronger than low-carbon steels

• But sacrifice of ductility and toughness

• Good wear resistance
Medium-Carbon Steels

- Railway wheels and tracks
- Gears
- Crankshafts
High-Carbon Steels

- Carbon contents **between 0.60 and 1.4 wt%**
- **Hardest, strongest and least ductile** of the carbon steels
- Wear resistant
- Tool and die steels
- Alloying elements combined with carbon to form very hard, wear resistant carbide compounds
High-Carbon Steels

- Cutting tools and dies for forming and shaping materials
- Knives
- Razors
- Hacksaw blades
- Springs
- High-strength wire
Stainless Steels

- Highly resistant to corrosion
- Predominant alloying element is chromium (Cr)
- A concentration of at least 11 wt% Cr
- Corrosion resistant may be enhanced by nickel and molybdenum
Stainless Steels

- Milled into coils, sheets, plates, bars, wire, and tubing
- Cookware
- Surgical instruments
- Automotive and aerospace
- Buildings as construction material
- Storage tanks and tanker because of its corrosion resistance and antibacterial properties
- Jewelry and watches

The 630-foot-high (190 m), stainless-clad (type 304) Gateway Arch defines St. Louis's skyline.
Ferrous Alloys

Iron containing – Steels - cast irons

Nomenclature  AISI & SAE

10xx Plain Carbon Steels
11xx Plain Carbon Steels (resulfurized for machinability)
15xx Mn (10 ~ 20%)
40xx Mo (0.20 ~ 0.30%)
43xx Ni (1.65 - 2.00%), Cr (0.4 - 0.90%), Mo (0.2 - 0.3%)
44xx Mo (0.5%)

where xx is wt% C x 100

example: 1060 steel – plain carbon steel with 0.60 wt% C

Stainless Steel -- >11% Cr
Cast Iron

- Ferrous alloys with > 2.1 wt% C
  - more commonly 3 - 4.5 wt% C
- low melting (also brittle) so easiest to cast

- Cementite decomposes to ferrite + graphite
  \[ \text{Fe}_3\text{C} \rightarrow 3 \text{Fe} (\alpha) + \text{C} \text{ (graphite)} \]
  - generally a slow process
Graphite formation promoted by

- Si > 1 wt%
- slow cooling

Adapted from Fig. 11.2, Callister 7e. (Fig. 11.2 adapted from Binary Alloy Phase Diagrams, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)
Cast Iron

- Class of ferrous alloys with carbon content above 2.14 wt%
- Higher carbon contents than steel
- Most cast irons contain between 3.0 and 4.5 wt% C and in addition other alloying elements, notably silicon.
- Most of the carbon exists in graphite form rather than combined with iron as cementite
Cast Iron

- Melting temperatures are app. 1150 and 1300°C which is lower than for steels.
- Thus easily melted and amenable to casting.
- Some cast irons are very brittle
Types of Cast Iron

- Gray Cast Iron
- White Cast Iron
- Nodular (Ductile) Cast Iron
- Malleable Cast Iron
Types of Cast Iron

Gray iron

- oldest and most common form
- graphite flakes
- weak & brittle under tension
- stronger under compression
- excellent vibrational dampening
- wear resistant
- high thermal conductivity and specific heat capacity

Adapted from Fig. 11.3(a), Callister 7e.
Types of Cast Iron

Gray iron
Applications when strength is not a primary consideration

- Small cylinder blocks, cylinder heads, pistons, transmission cases
- Diesel engine castings, liners
- Cast iron cookware

Close-up of a disc brake on a car

On automobiles, disc brakes are often located within the wheel
Types of Cast Iron

Ductile iron

- add Mg or Ce to the gray iron
- Different microstructure and mechanical properties
- graphite in nodules not flakes
- matrix often pearlite - better ductility

Adapted from Fig. 11.3 (b), Callister 7e.
Ductile iron

- Pipes
- Valves, pump bodies, crankshafts,
- Rollers, slides
- High-strength gears
- Other automotive and machine components

How to make ductile iron pipes?
White iron

- <1wt% Si so harder but brittle
- Carbon exists as a cementite instead of a graphite
- Limited using because of its extreme hardness and brittleness
Types of Cast Iron

White iron

- Limited using because of its extreme hardness and brittleness
- Applications which necessitate a very hard and wear resistant surface without a high degree of ductility
- Rollers and rolling mills

Adapted from Fig. 11.3(c) *Callister 7e.*
Types of Cast Iron

**Malleable iron**

- Heat treat at 800-900°C
- graphite in rosettes
- High strength
- more ductile

Adapted from Fig. 11.3 (d), *Callister 7e*.
Malleable iron

- Connecting rods, transmission gears,
- Automotive industry
- Pipe fittings, valve parts for marine, railroad
- Heavy-duty services
Production of Cast Iron

Reheat: hold at ~700°C for 30 + h

Fast cool: $P + Fe_3C$
Slow cool: $P + Gr$

Fast cool: White cast iron
Moderate: Pearlitic gray cast iron
Slow cool: Ferritic gray cast iron

Moderate: $P + Gn$
Slow cool: $\alpha + Gn$

Pearlitic malleable
Ferritic malleable

Adapted from Fig.11.5, Callister 7e.
Limitations of Ferrous Alloys

1) Relatively high density
2) Relatively low conductivity
3) Poor corrosion resistance
Nonferrous Alloys

Steel and other ferrous alloys are consumed in exceedingly large quantities because they have wide range of mechanical properties.

However, steel and ferrous alloys have some limitations:

- Relatively high density
- Comparatively low electrical conductivity
- Inherent susceptibility to corrosion in some common environments

- Alloy systems are classified either according to the base metal or according to some characteristics.
Nonferrous Alloys

- Cu Alloys
  Brass: Zn is subst. impurity (costume jewelry, coins, corrosion resistant)
  Bronze: Sn, Al, Si, Ni are subst. impurity (bushings, landing gear)
  Cu-Be: precip. hardened for strength

- Al Alloys
  -lower $\rho$: 2.7g/cm$^3$
  -Cu, Mg, Si, Mn, Zn additions
  -solid sol. or precip. strengthened (struct. aircraft parts & packaging)

- Mg Alloys
  -very low $\rho$: 1.7g/cm$^3$
  -ignites easily
  -aircraft, missiles

- Ti Alloys
  -lower $\rho$: 4.5g/cm$^3$
  vs 7.9 for steel
  -reactive at high $T$
  -space applic.

- Noble metals
  -Ag, Au, Pt
  -oxid./corr. resistant

- Refractory metals
  -high melting $T$
  -Nb, Mo, W, Ta

Based on discussion and data provided in Section 11.3, Callister 7e.
Copper

- Unalloyed copper is too soft and ductile to machine
- Very high thermal conductivity and electrical conductivity.
- Highly resistant to corrosion in diverse environments such as ambient atmosphere, sea water, and some industrial chemicals
Copper Alloys

- Mechanical and corrosion-resistant properties may be improved by alloying.

- Most common copper alloys are brasses where zinc is predominant alloying element.

- Bronze where tin is used as an alloying element.
Copper and Copper Alloys

- Jet aircraft landing gear bearings and bushings
- Springs
- Surgical and dental instruments
Chapter 11 - Nonferrous Alloys

Aluminum

- The third most abundant element after oxygen and silicon
- Relatively low density
- High electrical and thermal conductivities
- A resistance to corrosion
- Easily formed because of their ductility
- Low melting point (660°C)
Aluminum Alloys

- Mechanical strength of aluminum may be enhanced by alloying
- Principal alloying elements are copper, magnesium, silicon, manganese, and zinc.
- Two classifications: wrought and cast Al-alloys
Nonferrous Alloys

Aluminum Alloys

- Most widely used nonferrous alloys
- Global production of Al in 2005 was 31.9 million tones

- Transportation (automobiles, aircraft, trucks, railway cars, marine vessels, bicycles, etc.) as sheet, tube, castings, etc.
- Packaging (cans, foil)
- Construction (windows, doors, siding, building wire, etc.)
- Electrical transmission lines for power distribution
Magnesium and Magnesium Alloys

- Light weight
- Lowest density (1.7 g/cm³) of all the structural metals
- At room temperature, it is difficult to deform Mg
- Good high temperature mechanical properties
- Good to excellent corrosion resistance
Magnesium and Magnesium Alloys

- Aircraft and missiles
- iPhone 5’s body consists of a single Magnesium-alloy based casing which holds the electronics that is itself sandwiched between two pieces of glass.

*Magnesium alloys are used to fabricate a variety of automotive components.*
Metal Fabrication

• How do we fabricate metals?
  – Blacksmith - hammer (forged)
  – Molding - cast

• Forming Operations
  – Rough stock formed to final shape

<table>
<thead>
<tr>
<th>Hot working</th>
<th>vs.</th>
<th>Cold working</th>
</tr>
</thead>
<tbody>
<tr>
<td>• $T$ high enough for recrystallization</td>
<td>• well below $T_m$</td>
<td>• work hardening</td>
</tr>
<tr>
<td>• Larger deformations</td>
<td>• smaller deformations</td>
<td></td>
</tr>
</tbody>
</table>
Processing of Metal Alloys

Metal fabrication techniques

Forming operations
- Forging
- Rolling
- Extrusion
- Drawing

Casting
- Sand
- Die
- Investment
- Lost foam
- Continuous

Miscellaneous
- Powder metallurgy
- Welding
Fabrication Techniques

WHICH METHOD???

Depends on several factors, such as
- the properties of the metal
- the size and the shape of the finished piece
- cost
Processing of Metal Alloys

Forming Operations
Shape of a metal is changed by plastic deformation

- Forging
- Rolling
- Extrusion
- Drawing
Metal Fabrication Methods - I

FORMING

- Forging (Hammering; Stamping) (wrenches, crankshafts)
  - force 
  - Often at elev. T

- Drawing (rods, wire, tubing)
  - die must be well lubricated & clean

CASTING

- Extrusion (rods, tubing)
  - Ductile metals, e.g. Cu, Al (hot)

JOINING

- Rolling (Hot or Cold Rolling) (I-beams, rails, sheet & plate)
  - Adapted from Fig. 11.8, Callister 7e.
Forging (Hammering; Stamping) (wrenches, crankshafts)

The metal is deformed in the cavity between die halves.

Let's watch a forging video!!!
Rolling

Most widely used deformation process
(I-beams, rails, sheet & plate)

Passing a piece of metal between two rolls; a reduction in thickness results from compressive stresses exerted by the rolls.

A coil of hot-rolled steel
Extrusion
(rods, tubing)

ductile metals, e.g. Cu, Al (hot)

A bar of metal is forced through a die orifice by compressive force
Pulling of a metal piece through a die by a tensile force that is applied on the exit side.

die must be well lubricated & clean
Metal Fabrication Methods - II

FORMING  CASTING  JOINING

• Casting - mold is filled with metal
  – metal melted in furnace, perhaps alloying elements added. Then cast in a mold
  – most common, cheapest method
  – gives good production of shapes
  – weaker products, internal defects
  – good option for brittle materials
Processing of Metal Alloys

Casting

Poring molten metal into a mold cavity having the desired shape.
• **Sand Casting**
  (large parts, e.g., auto engine blocks)

- trying to hold something that is hot
- what will withstand >1600ºC?
- cheap - easy to mold => sand!!!
- pack sand around form (pattern) of desired shape
Sand Casting
Most common casting method (Over 70% of all metal castings)
Ordinary sand is used as the mold material

Let’s watch a sand casting video!!!

Two sets of castings (bronze and aluminium) from the above sand mold
### Metal Fabrication Methods - II

**FORMING**

- **Sand Casting**
  (large parts, e.g., auto engine blocks)

**CASTING**

- **Investment Casting**
  (low volume, complex shapes e.g., jewelry, turbine blades)
  - pattern is made from paraffin.
  - mold made by encasing in plaster of paris
  - melt the wax & the hollow mold is left
  - pour in metal

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**JOINING**

- Sand
  - Sand
  - molten metal
Metal Fabrication Methods - II

- **Sand Casting**
  (large parts, e.g., auto engine blocks)

- **Investment Casting**
  (low volume, complex shapes e.g., jewelry, turbine blades)

- **Die Casting**
  (high volume, low T alloys)

- **Continuous Casting**
  (simple slab shapes)
Metal Fabrication Methods - III

FORMING

- **Powder Metallurgy**
  (materials w/low ductility)
  - point contact at low $T$
  - densify
  - pressure
  - heat
  - area contact
  - densification by diffusion at higher $T$

CASTING

- **Welding**
  (when one large part is impractical)
  - filler metal (melted)
  - base metal (melted)
  - fused base metal
  - unaffected
  - heat affected zone

JOINING

- **Heat affected zone**:
  (region in which the microstructure has been changed).

Adapted from Fig. 11.9, *Callister 7e*. (Fig. 11.9 from *Iron Castings Handbook*, C.F. Walton and T.J. Opar (Ed.), 1981.)
Powder Metallurgy

(materials w/ low ductility)

- Blending fine powdered materials,
- pressing them into a desired shape or form (compacting), and then
- heating the compressed material in a controlled atmosphere to bond the material (sintering).

Rhodium metal: powder, pressed pellet (3*10^5 psi), remelted
Welding
(when one large part is impractical)

- Heat affected zone:
  (region in which the microstructure has been changed).

The blue area results from oxidation at a corresponding temperature of 600 °F (316 °C).

Let’s watch a welding video!!!
Thermal Processing of Metals

Annealing: Heat to $T_{\text{anneal}}$, then cool slowly.

- **Stress Relief**: Reduce stress caused by:
  - plastic deformation
  - nonuniform cooling
  - phase transform.

- **Process Anneal**: Negate effect of cold working by (recovery/recrystallization)

- **Spheroidize** (steels): Make very soft steels for good machining. Heat just below $T_E$ & hold for 15-25 h.

- **Full Anneal** (steels): Make soft steels for good forming by heating to get $\gamma$, then cool in furnace to get coarse $P$.

- **Normalize** (steels): Deform steel with large grains, then normalize to make grains small.

Based on discussion in Section 11.7, *Callister 7e.*
Heat Treatments

a) Annealing
b) Quenching
c) Tempered Martensite

Adapted from Fig. 10.22, Callister 7e.
Hardenability--Steels

- Ability to form martensite
- Jominy end quench test to measure hardenability.

Adapted from Fig. 11.11, *Callister 7e*. (Fig. 11.11 adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1978.)

- Hardness versus distance from the quenched end.

Adapted from Fig. 11.12, *Callister 7e.*
Quenching Medium & Geometry

- Effect of quenching medium:
  - Medium: air, oil, water
  - Severity of Quench: low, moderate, high
  - Hardness: low, moderate, high

- Effect of geometry:
  - When surface-to-volume ratio increases:
    --cooling rate increases
    --hardness increases

  - Position: center, surface
    - Cooling rate: low, high
    - Hardness: low, high
Metal Alloy Crystal Structure

Alloys

• substitutional alloys
  – can be ordered or disordered
  – disordered solid solution
  – ordered - periodic substitution

example: CuAu    FCC

\[ \text{Cu} \quad \text{Au} \]
Metal Alloy Crystal Structure

- Interstitial alloys (compounds)
  - one metal much larger than the other
  - smaller metal goes in ordered way into interstitial “holes” in the structure of larger metal
  - Ex: Cementite – Fe₃C
Metal Alloy Crystal Structure

- Consider FCC structure --- what types of holes are there?

Octahedron - octahedral site = $O_H$

Tetrahedron - tetrahedral site = $T_D$
Metal Alloy Crystal Structure

- Interstitials such as H, N, B, C
- FCC has 4 atoms per unit cell
  - 4 $O_H$ sites
  - 8 $T_D$ sites

![Diagram](image)

metal atoms

$O_H$ sites

$T_D$ sites
Summary

- Steels: increase TS, Hardness (and cost) by adding
  --C (low alloy steels)
  --Cr, V, Ni, Mo, W (high alloy steels)
  --ductility usually decreases w/additions.
- Non-ferrous:
  --Cu, Al, Ti, Mg, Refractory, and noble metals.
- Fabrication techniques:
  --forming, casting, joining.
- Hardenability
  --increases with alloy content.
- Precipitation hardening
  --effective means to increase strength in Al, Cu, and Mg alloys.
ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: