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?
Taxonomy of Metals

Adapted from Fig. 11.1, Callister 7e.

Metal Alloys

Ferrous

Nonferrous

Steels

<1.4 wt% C

Cast Irons

3-4.5 wt% C

Cu

Al

Mg

Ti

microstructure:
ferrite, graphite
cementite

Adapted from Fig. 9.24, Callister 7e. (Fig. 9.24 adapted from Binary Alloy Phase Diagrams, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)
11.1 Ferrous alloys

Iron containing – Steels - cast irons

Nomenclature  AISI & SAE

10xx Plain Carbon Steels
11xx Plain Carbon Steels (resulfurized for machinability)
12xx Plain Carbon Steels (Resulfurized and rephosphorized)
13xx Mn (1.6-1.9%)
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
<table>
<thead>
<tr>
<th>AISI-SAE Designation Number</th>
<th>Type and Description</th>
<th>Steel Alloy Designation System (American Iron and Steel Institute-Society of Automotive Engineering)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10xx</td>
<td>Plain Carbon (Mn. 1.00% max.)</td>
<td></td>
</tr>
<tr>
<td>11xx</td>
<td>Resulfurized</td>
<td></td>
</tr>
<tr>
<td>12xx</td>
<td>Resulfurized and rephosphorized</td>
<td></td>
</tr>
<tr>
<td>15xx</td>
<td>Plain Carbon (max. Mn. range 1.00-1.65%)</td>
<td></td>
</tr>
<tr>
<td>13xx</td>
<td>Mn 1.75</td>
<td></td>
</tr>
<tr>
<td>23xx</td>
<td>Ni 3.50</td>
<td></td>
</tr>
<tr>
<td>25xx</td>
<td>Ni 5.00</td>
<td></td>
</tr>
<tr>
<td>31xx</td>
<td>Ni 1.25; Cr 0.65, 0.80</td>
<td></td>
</tr>
<tr>
<td>32xx</td>
<td>Ni 1.75; Cr 1.07</td>
<td></td>
</tr>
<tr>
<td>33xx</td>
<td>Ni 3.50; Cr 1.50, 1.57</td>
<td></td>
</tr>
<tr>
<td>34xx</td>
<td>Ni 3.00; Cr 0.77</td>
<td></td>
</tr>
<tr>
<td>40xx</td>
<td>Mo 0.20, 0.25</td>
<td></td>
</tr>
<tr>
<td>44xx</td>
<td>Mo 0.40, 0.52</td>
<td></td>
</tr>
<tr>
<td>41xx</td>
<td>Cr 0.50, 0.80, 0.95; Mo 0.12, 0.20, 0.25, 0.30</td>
<td></td>
</tr>
<tr>
<td>43xx</td>
<td>Ni 1.82; Cr 0.50, 0.80; Mo 0.25</td>
<td></td>
</tr>
<tr>
<td>43BVxx</td>
<td>Ni 1.82; Cr 0.50; Mo 0.12, 0.25; V 0.03 min.</td>
<td></td>
</tr>
<tr>
<td>47xx</td>
<td>Ni 1.05; Cr 0.45; Mo 0.20, 0.35</td>
<td></td>
</tr>
</tbody>
</table>

http://www.engineershandbook.com/Tables/carbonsteelalloys.htm
<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>81xx</td>
<td>0.30</td>
<td>0.40</td>
<td>0.12</td>
</tr>
<tr>
<td>86xx</td>
<td>0.55</td>
<td>0.50</td>
<td>0.20</td>
</tr>
<tr>
<td>87xx</td>
<td>0.55</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>88xx</td>
<td>0.55</td>
<td>0.50</td>
<td>0.35</td>
</tr>
<tr>
<td>93xx</td>
<td>3.25</td>
<td>1.20</td>
<td>0.12</td>
</tr>
<tr>
<td>94xx</td>
<td>0.45</td>
<td>0.40</td>
<td>0.12</td>
</tr>
<tr>
<td>97xx</td>
<td>1.00</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>98xx</td>
<td>1.00</td>
<td>0.80</td>
<td>0.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nickel-molybdenum steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>46xx Ni 0.85, 1.82; Mo 0.20, 0.25</td>
</tr>
<tr>
<td>48xx Ni 3.50; Mo 0.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chromium steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>50xx Cr 0.27, 0.40, 0.50, 0.65</td>
</tr>
<tr>
<td>51xx Cr 0.80, 0.87, 0.92, 0.95, 1.00, 1.05</td>
</tr>
<tr>
<td>50xxx Cr 0.50; C 1.00 min.</td>
</tr>
<tr>
<td>51xxx Cr 1.02; C 1.00 min.</td>
</tr>
<tr>
<td>52xxx Cr 1.45; C 1.00 min.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chromium-vanadium steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>61xx Cr 0.60, 0.80, 0.95; V 0.10, 0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tungsten-chromium steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>72xx W 1.75; Cr 0.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Silicon-manganese steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>92xx Si 1.40, 2.00; Mn 0.65, 0.82, 0.85; Cr 0.00, 0.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High-strength low-alloy steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>9xx Various SAE grades</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Boron steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxBxx B denotes boron steels</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leaded steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxLxx L denotes leaded steels</td>
</tr>
</tbody>
</table>
# Steels

## Low Alloy

**Low Carbon**
- <0.25wt% C

**Medium Carbon**
- 0.25-0.6wt% C

**High Carbon**
- 0.6-1.4wt% C

## High Alloy

**Austenitic Stainless**
- Cr, Ni, Mo (>11%)

<table>
<thead>
<tr>
<th>Name</th>
<th>plain</th>
<th>HSLA</th>
<th>plain heat treatable</th>
<th>plain tool</th>
<th>austenitic stainless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additions</td>
<td>none</td>
<td>Cr, V, Ni, Mo</td>
<td>Cr, Ni, Mo</td>
<td>Cr, V, Mo, W</td>
<td>Cr, Ni, Mo (&gt;11%)</td>
</tr>
<tr>
<td>Example</td>
<td>1010</td>
<td>4310</td>
<td>1040</td>
<td>4340</td>
<td>1095</td>
</tr>
<tr>
<td>Hardenability</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>TS</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>EL</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Uses</td>
<td>auto struc.</td>
<td>bridges towers press. vessels</td>
<td>crank shafts bolts hammers blades</td>
<td>pistons gears wear applic.</td>
<td>wear applic.</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 → BLAST FURNACE

- **Heat Generation**
  - \( C + O_2 \rightarrow CO_2 \)

- **Reduction of Iron Ore to Metal**
  - \( CO_2 + C \rightarrow 2CO \)
  - \( 3CO + Fe_2O_3 \rightarrow 2Fe + 3CO_2 \)

- **Purification**
  - \( CaCO_3 \rightarrow CaO + CO_2 \)
  - \( CaO + SiO_2 + Al_2O_3 \rightarrow \text{slag} \)

Layers of coke and iron ore → gas in refractory vessel → Heated air → slag → Molten iron
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
  \[ \text{Fe}_3\text{C} \rightarrow \alpha + \text{graphte} \]
- generally a slow process

Eutectic:
\[ 4.30 \text{ wt% C} \rightarrow \gamma + \text{L} \]
\[ 1148^\circ \text{C} \]

Eutectoid:
\[ 0.76 \text{ wt% C} \rightarrow \alpha + \text{Fe}_3\text{C} \]
\[ 727^\circ \text{C} \]
Fe-C True Equilibrium Diagram

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.)
Types of Cast Iron

Gray iron
(2.5-4.0wt%C and 1.0-3.0wt%Si)
- graphite flakes+ferrite
- weak & brittle under tension
- stronger under compression
- excellent vibrational dampening
- wear resistant

Ductile iron
- add Mg or Ce to Gray iron
- graphite in nodules not flakes
- matrix often pearlite - better ductility

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

White iron
- <1wt% Si rapid cooling
- more cementite instead of graphite + pearlite
- harder but brittle

Malleable iron
- heat treat white iron at 800-900°C (cementite decomposes).
- graphite in rosettes
- more ductile

Adapted from Fig. 11.3(c) & (d), Callister 7e.
Production of Cast Iron

Adapted from Fig. 11.5, Callister 7e.

Reheat: hold at ~700°C for 30 + h

<table>
<thead>
<tr>
<th>Fast cool</th>
<th>Moderate</th>
<th>Slow cool</th>
</tr>
</thead>
<tbody>
<tr>
<td>P + Fe₃C</td>
<td>P + Gf</td>
<td>α + Gf</td>
</tr>
</tbody>
</table>

Mg/Ce

<table>
<thead>
<tr>
<th>Moderate</th>
<th>Slow cool</th>
</tr>
</thead>
<tbody>
<tr>
<td>P + Gₙ</td>
<td>α + Gₙ</td>
</tr>
</tbody>
</table>

White cast iron
Pearlitic gray cast iron
Ferritic gray cast iron
Pearlitic ductile cast iron
Ferritic ductile cast iron
Limitations of Ferrous Alloys

1) Relatively high density
2) Relatively low conductivity
3) Poor corrosion resistance
11.3 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 ρ: 2.7g/cm³
  - Cu, Mg, Si, Mn, Zn additions
  - solid sol. or precip. strengthened (struct. aircraft parts & packaging)

- **Mg Alloys**
  - very low ρ: 1.7g/cm³
  - ignites easily
  - aircraft, missiles

- **Ti Alloys**
  - lower ρ: 4.5g/cm³ 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
  - Strong interatomic B

---

Based on discussion and data provided in Section 11.3, *Callister 7e.*
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</td>
<td></td>
<td>well below $T_m$</td>
</tr>
<tr>
<td>for recrystallization</td>
<td></td>
<td>work hardening</td>
</tr>
<tr>
<td>Larger deformations</td>
<td></td>
<td>smaller deformations</td>
</tr>
<tr>
<td>Risk of surface oxidation</td>
<td></td>
<td>better surface finish</td>
</tr>
</tbody>
</table>
11.4
Metal Fabrication Methods - I

FORMING

- Forging (Hammering; Stamping) (wrenches, crankshafts)
  force

  \[ A_0 \rightarrow A_d \]

  Often at elev. T

- Drawing (rods, wire, tubing)
  \[ A_0 \rightarrow A_d \]
  Tensile force

  Die must be well lubricated & clean

CASTING

JOINING

- Rolling (Hot or Cold Rolling) (I-beams, rails, sheet & plate)

  \[ A_0 \rightarrow A_d \]

  Adapted from Fig. 11.8, Callister 7e.

- Extrusion (rods, tubing)

  \[ A_0 \rightarrow A_d \]

  Ductile metals, e.g. Cu, Al (hot)
  Die holder
  Extrusion
  \[ A_0 \rightarrow A_d \]

Chapter 11 - 16
11.5 Metal Fabrication Methods - II

- **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
Metal Fabrication Methods - II

FORMING

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

CASTING

• trying to hold something that is hot
• what will withstand >1600°C?
• cheap - easy to mold => sand!!!
• pack sand around form (pattern) of desired shape

JOINING
Metal Fabrication Methods - II

FORMING

CASTING

JOINING

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

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

**Investment Casting**
- pattern is made from paraffin.
- mold made by encasing in plaster of paris
- melt the wax & the hollow mold is left
- pour in metal
Metal Fabrication Methods - II

FORMING

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

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

CASTING

• Die Casting
  (high volume, low T alloys)

• Continuous Casting
  (simple slab shapes)

JOINING
11.6 Metal Fabrication Methods - III

**FORMING**

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

**CASTING**

- **Welding**
  (when one large part is impractical)
  - filler metal (melted)
  - base metal (melted)
  - fused base metal
  - 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.)
Homework Assignment

11.1
11.6
11.10
11.29
11.D10
Thermal Processing of Metals

11.7 Annealing: Heat to \( T_{\text{anneal}} \), soak, then cool slowly.

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

- **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 \( P \).

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

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

Based on discussion in Section 11.7, *Callister 7e.*
11.8 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.
Why Hardness Changes W/Position

• The cooling rate varies with position.

Adapted from Fig. 11.13, *Callister 7e*. (Fig. 11.13 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 376.)
Hardenability vs Alloy Composition

• Jominy end quench results, $C = 0.4$ wt% C

Adapted from Fig. 11.14, Callister 7e. (Fig. 11.14 adapted from figure furnished courtesy Republic Steel Corporation.)

• "Alloy Steels" (4140, 4340, 5140, 8640)  
  --contain Ni, Cr, Mo (0.2 to 2wt%)  
  --these elements shift the "nose".  
  --martensite is easier to form.
Quenching Medium & Geometry

- Effect of quenching medium:
  
<table>
<thead>
<tr>
<th>Medium</th>
<th>Severity of Quench</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>oil</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>water</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Position</th>
<th>Cooling rate</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>center</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>surface</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>
Chapter 11 -

Mildly agitated water

Mildly agitated oil
11.9 Precipitation Hardening

- Particles impede dislocations.
- Ex: Al-Cu system
- Procedure:
  - Pt A: solution heat treat (get $\alpha$ solid solution)
  - Pt B: quench to room temp.
  - Pt C: reheat to nucleate small $\theta$ crystals within $\alpha$ crystals.
- Other precipitation systems:
  - Cu-Be
  - Cu-Sn
  - Mg-Al

Adapted from Fig. 11.22, Callister 7e.

Adapted from Fig. 11.24, Callister 7e. (Fig. 11.24 adapted from J.L. Murray, International Metals Review 30, p.5, 1985.)
Precipitate Effect on TS, %EL

• 2014 Al Alloy:
  • TS peaks with precipitation time.
  • Increasing $T$ accelerates process.
  • %EL reaches minimum with precipitation time.

Adapted from Fig. 11.27 (a) and (b), Callister 7e. (Fig. 11.27 adapted from Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals, Vol. 2, 9th ed., H. Baker (Managing Ed.), American Society for Metals, 1979. p. 41.)
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.