Outline

• Introduction: Relative cost of materials
• Non Ferrous Alloys
  - Copper alloys
  - Aluminum and its alloys
  - Magnesium and its alloys
  - Titanium and its alloys
  - Nickel and its alloys
  - Superalloys
• Miscellaneous Nonferrous Alloys
• Summary

Approximate Cost Per Unit Volume for Wrought Metals and Plastics Relative to Carbon Steel

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost / Cost of Carbon Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>.............................</td>
</tr>
<tr>
<td>Silver</td>
<td>600</td>
</tr>
<tr>
<td>Mo Alloys</td>
<td>200-250</td>
</tr>
<tr>
<td>Nickel</td>
<td>.............................</td>
</tr>
<tr>
<td>Ti Alloys</td>
<td>20-40</td>
</tr>
<tr>
<td>Cu Alloys</td>
<td>5-6</td>
</tr>
<tr>
<td>Zinc Alloys</td>
<td>1.5-3.5</td>
</tr>
<tr>
<td>Stainless Steels</td>
<td>2-9</td>
</tr>
<tr>
<td>Mg Alloys</td>
<td>2-4</td>
</tr>
<tr>
<td>Al Alloys</td>
<td>2-3</td>
</tr>
<tr>
<td>High Strength Steels</td>
<td>1.4</td>
</tr>
<tr>
<td>Gray Cast Iron</td>
<td>1.2</td>
</tr>
<tr>
<td>Nylons, silicon rubber</td>
<td>1.1-2</td>
</tr>
<tr>
<td>Plastics/Elastomers</td>
<td>0.2-1</td>
</tr>
<tr>
<td>Fiber Composites</td>
<td>.............................</td>
</tr>
</tbody>
</table>

Non-Ferrous Alloys

Steel & other ferrous alloys are used in very large quantities but:

• have relatively high densities
• relatively low electrical conductivity
• susceptibility to corrosion in many atmospheres

Wrought Alloys and Cast alloys:

✓ Copper & alloys (including brasses, bronzes)
✓ Aluminum & alloys
✓ Magnesium
✓ Titanium
✓ Nickel
✓ Lead
✓ Zinc
✓ Tin ...

Copper Alloys

• Density; 8.93 Mg/m³ so alloys are heavier than steel.
• Specific strength not very high
• Good ductility, (very soft when pure).
• Corrosion resistant (some surface reactions)
• Relatively good fatigue, creep and wear resistance compared to Al alloys.
• High electrical and thermal conductivity.
• Easily joined and fabricated.

Strengthening:

✓ Cold-working: principle method for most alloys
✓ Solid solution: - Cu-Zn, Cu-Sn, Cu-Al, Cu-Be
✓ Age-hardenable: - Cu-Zr, Cu-Be
✓ Phase transformations: - Cu-Al
Copper Alloys

- Strength and hardness of copper is relatively low; to improve strength, copper is frequently alloyed
- **Bronze** - alloy of copper and tin (typically ~ 90% Cu, 10% Sn), widely used today and in ancient times (i.e., the Bronze Age)
  - Additional bronzes include aluminum bronzes and silicon bronzes
- **Brass** - alloy of copper and zinc (typically ~ 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
- Based on the Unified Numbering System for Metals and Alloys (UNS), which uses a five digit number preceded by the letter C.
- Includes both wrought and cast copper and its 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)

### Brasses Cu-Zn alloys

- Several phases: \( \alpha \) (FCC) - soft, ductile, easily cold-worked.
- \( \beta \) is BCC, harder & stronger than \( \alpha \).
- 60-40 brass is \((\alpha + \beta)\).

### Table 12.6 Compositions, Mechanical Properties, and Typical Applications for Eight Copper Alloys

<table>
<thead>
<tr>
<th>Alloy Name</th>
<th>UNS Number</th>
<th>Composition (wt% Cu)</th>
<th>Condition</th>
<th>Tensile Strength (MPa [ksi])</th>
<th>Yield Strength (MPa [ksi])</th>
<th>Ductility [% El. in 50 mm]</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bronze: Cu + Sn, Al, Si, Ni</td>
<td></td>
<td>Stronger than brasses and still good corrosion resistance.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation hardenable - e.g. Cu-Be - very high strength, corrosion &amp; wear resistant... etc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Copper Alloys**

<table>
<thead>
<tr>
<th>Alloy Name</th>
<th>UNS Number</th>
<th>Composition (wt% Cu)</th>
<th>Condition</th>
<th>Tensile Strength (MPa [ksi])</th>
<th>Yield Strength (MPa [ksi])</th>
<th>Ductility [% El. in 50 mm]</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead rich brass</td>
<td>C65400</td>
<td>29 Zn, 3 Pb, 1 Sn</td>
<td>As cast</td>
<td>254 (34)</td>
<td>85 (12)</td>
<td>35</td>
<td>Furniture hardware, radiator fittings, light fixtures, battery clamps</td>
</tr>
<tr>
<td>Tin bronze</td>
<td>C90500</td>
<td>10 Sn, 2 Zn</td>
<td>As cast</td>
<td>310 (45)</td>
<td>152 (22)</td>
<td>25</td>
<td>Bearings, bushings, piston rings, vacuum fittings, gears</td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td>C95400</td>
<td>4 Fe, 11 Al</td>
<td>As cast</td>
<td>586 (85)</td>
<td>241 (35)</td>
<td>18</td>
<td>Bearings, gears, washers, bushings, valve seats and guides, pickling hooks</td>
</tr>
</tbody>
</table>

*The balance of the composition is copper.*
Aluminum and Its Alloys

- Low Density: 2.7 Mg/m³ (Steel 7.87 Mg/m³)
- Pure Al is very soft and ductile but alloys of strengths of 690 MPa are possible by combining cold working, alloying, and precipitation hardening mechanisms.
- Many alloys very ductile/workable even at low temperatures (FCC).
- Gives good specific strength: σ/ρ
- Good Corrosion Resistance: Aluminium oxide film on surface protects metal.
- Also aluminum:
  ✓ Non-toxic
  ✓ High electrical conductivity
  ✓ High thermal conductivity
  ✓ Non-magnetic
  ✓ No fatigue limit
  ✓ Low melting point (660°C) restricts operating temp. but facilitates casting.
  ✓ Low hardness/wear resistance

Designations of Wrought and Cast Al Alloys

<table>
<thead>
<tr>
<th>Alloy group</th>
<th>Wrought code</th>
<th>Cast code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum ≥ 99.0% purity</td>
<td>1XXX</td>
<td>1XX.X</td>
</tr>
<tr>
<td>Copper alloy</td>
<td>2XXX</td>
<td>2XX.X</td>
</tr>
<tr>
<td>Manganese alloy</td>
<td>3XXX</td>
<td></td>
</tr>
<tr>
<td>Silicon alloy</td>
<td>4XXX</td>
<td>4XX.X</td>
</tr>
<tr>
<td>Zinc alloy</td>
<td>7XXX</td>
<td>7XX.X</td>
</tr>
<tr>
<td>Tin alloy</td>
<td></td>
<td>8XX.X</td>
</tr>
</tbody>
</table>

- 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

Wrought, Non-Hardened Alloys

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility [%EL in 30 mm (2 in.)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>50 (7)</td>
<td>50 (7)</td>
<td>35-45 (12-16)</td>
</tr>
<tr>
<td>H</td>
<td>120 (17)</td>
<td>120 (17)</td>
<td>15-20 (6-8)</td>
</tr>
<tr>
<td>O</td>
<td>200 (30)</td>
<td>200 (30)</td>
<td>10-15 (4-6)</td>
</tr>
<tr>
<td>T</td>
<td>250 (36)</td>
<td>250 (36)</td>
<td>5-10 (2-4)</td>
</tr>
</tbody>
</table>

Table 12.7 Compositions, Mechanical Properties, and Typical Applications for Several Common Aluminum Alloys

<table>
<thead>
<tr>
<th>Alloy Group</th>
<th>UNS Number</th>
<th>Composition [wt%]</th>
<th>Condition</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility [%EL in 50 mm (2 in.)]</th>
</tr>
</thead>
</table>
| Cu increases strength, but >0.5% reduces corrosion resistance

Wrought, Heat-Treatable Alloys

<table>
<thead>
<tr>
<th>Aluminum Association Number</th>
<th>UNS Number</th>
<th>Composition [wt%]</th>
<th>Condition</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility [%EL in 50 mm (2 in.)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024</td>
<td>A90024</td>
<td>4.6 Cu, 1.5 Mg, 0.6 Mn</td>
<td>Heat treated (T4)</td>
<td>470 (68)</td>
<td>325 (47)</td>
<td>20</td>
</tr>
<tr>
<td>6061</td>
<td>A90061</td>
<td>1.0 Mg, 0.6 Si, 0.2 Cu, 0.28 Cr</td>
<td>Heat treated (T4)</td>
<td>240 (35)</td>
<td>145 (21)</td>
<td>22-25</td>
</tr>
<tr>
<td>7075</td>
<td>A90055</td>
<td>5.6 Mg, 2.5 Mg, 1.6 Cu, 0.23 Cr</td>
<td>Heat treated (T6)</td>
<td>570 (83)</td>
<td>505 (73)</td>
<td>11</td>
</tr>
</tbody>
</table>

- Cu increases strength, but >0.5% reduces corrosion resistance
- Mn or Cr increases strength, grain size control

Temper Description

- 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

Aluminum and Its Alloys

- Advanced alloys - Al-Lithium

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<table>
<thead>
<tr>
<th>Aluminum Association Number</th>
<th>UNS Number</th>
<th>Composition [wt%]</th>
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Aluminum and Its Alloys

- Advanced alloys - Al-Lithium
Aluminum and Its Alloys

<table>
<thead>
<tr>
<th>Aluminum Association Number</th>
<th>UNS Number</th>
<th>Composition [wt%]</th>
<th>Condition (Temp Designation)</th>
<th>Tensile Strength [MPa (psi)]</th>
<th>Yield Strength [MPa (psi)]</th>
<th>Ductility [% EL at 50 mm (2 in.)]</th>
<th>Typical Applications/Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>205.0</td>
<td>A03500</td>
<td>4.5 Cu, 1.1 Si</td>
<td>Heat treated (T4)</td>
<td>221 (32)</td>
<td>110 (16)</td>
<td>8.5</td>
<td>Flywheel and rear-axle housings, bus and aircraft wheels, crankcases</td>
</tr>
<tr>
<td>336.0</td>
<td>A03500</td>
<td>7.0 Si, 0.3 Mg</td>
<td>Heat treated (T6)</td>
<td>228 (33)</td>
<td>164 (24)</td>
<td>3.5</td>
<td>Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks</td>
</tr>
</tbody>
</table>

**T4** – Solution heat-treated and naturally aged to a substantially stable condition

**T6** – Solution heat-treated and then artificially aged.

Magnesium and Its Alloys

- Very low density: 1.74 Mg/m³ (Al: 2.7 Mg/m³)
- HCP
- Relatively soft
- Low E (45 GPa) (but better than ………)
- But:
  - Expensive,
  - Difficult to cast,
  - Low strength,
  - Low creep, fatigue and wear resistance
  - Low room temp. ductility (hcp) so cold-working limited.

- Fabricated by casting - (melts at 651°C) or hot-working (200-350°C).
- Used for weight saving applications; Missiles, luggage, laptops, cellphones, chainsaws, cameras….

Magnesium and Its Alloys

**Designation of Magnesium Alloys**

- The principle alloying elements are aluminum (A), 9 percent and zinc (Z), 1 percent (note: the numbers are rounded off)
- The letter C, the third letter of the alphabet, indicates that this is the third alloy standardized, after A and B, which were the first and second alloys, respectively, that were standardized.
- T6 indicates that this alloy has been solution treated and artificially aged.
- The temper of the material, indicated by the same symbols used for Al-alloys

For example, the alloy AZ91C-T6

- The principle alloying elements are aluminum (A), 9 percent and zinc (Z), 1 percent (note: the numbers are rounded off)
- The letter C, the third letter of the alphabet, indicates that this is the third alloy standardized, after A and B, which were the first and second alloys, respectively, that were standardized.
- T6 indicates that this alloy has been solution treated and artificially aged.
- The temper of the material, indicated by the same symbols used for Al-alloys
Titanium and Its Alloys

- Medium density 4.54 Mg/m³ (steel 7.9 Mg/m³)
- High melting point (1668°C)
- But relatively strong. $\sigma_{YS} \approx 800$ MPa (max $\approx 1100$ MPa)
- Stiffer than Aluminium; 107 - 116 GPa vs 70 GPa but not as stiff as steel (207 GPa).
- Highly ductile
- Good corrosion resistance
- Good strength to weight ratio
- Expensive production due to reactivity at high temperature.

Almost all Ti alloys contain aluminum
- Al increases ductility, and
- reduces density

Titanium and Its Alloys

“Pure” titanium has lower strength, but more corrosion resistant and less expensive

<table>
<thead>
<tr>
<th>Alloy Type</th>
<th>Common Name (CAS Number)</th>
<th>Composition (wt%)</th>
<th>Condition</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility [%EL in 2 in]</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercially pure</td>
<td>Undeformed (R5100)</td>
<td>99.1 Ti</td>
<td>Annealed</td>
<td>481 (70)</td>
<td>41 (6)</td>
<td>25</td>
<td>Jet engine shroud, case and airframe skins, corrosion-resistant equipment for marine and chemical processing industries</td>
</tr>
<tr>
<td>α</td>
<td>Ti-6Al-4V (R5400)</td>
<td>6 Al, 4 V, balance Ti</td>
<td>Annealed</td>
<td>947 (137)</td>
<td>877 (127)</td>
<td>14</td>
<td>High-strength prosthetic implants, chemical process equipment, airframe structural components</td>
</tr>
<tr>
<td>α+β</td>
<td>Ti-6Al-2Sn-4Zr-2Mo-0.2Si (R5600)</td>
<td>6 Al, 2 Sn, 4 V, 0.25 Si, balance Ti</td>
<td>Annealed</td>
<td>1050 (155)</td>
<td>865 (135)</td>
<td>14</td>
<td>Rocket engine case airframe applications and high-strength airframe structures</td>
</tr>
<tr>
<td>β</td>
<td>Ti-6Al-2Sn-4Zr-2Mo-0.2Si (R5600)</td>
<td>6 Al, 2 Sn, 4 V, 0.25 Si, balance Ti</td>
<td>Solution + aging</td>
<td>1223 (176)</td>
<td>1130 (167)</td>
<td>10</td>
<td>Best combination of high strength and toughness of any commercial titanium alloy; used for applications requiring uniformity of tensile properties at surface and center locations; high-strength airframe components</td>
</tr>
</tbody>
</table>

Nickel and Its Alloys

- Nickel: FCC (tough and ductile)
- Good high and low temperature strength, high oxidation resistance
- Highly resistant to corrosion especially alkaline.
- Highly desirable material, but extremely expensive
- Primary Nickel reserves in …………….. and New Caledonia

- Nickel is often coated or plated on some metals that are susceptible to corrosion as a protective measure.
- **Monel**, (65 wt% Ni - 28 wt% Cu & Fe-balance), has very high strength and is extremely corrosion resistant; it is used in pumps, valves, and other components that are in contact with some acid and petroleum solutions. (also Ni is used in stainless steels and superalloys)
- Chromium improves corrosion resistance and mechanical properties at elevated temperature → **Inconel** series (Ni-Cr alloys)

Superalloys

- High temperature performance (strength)
- Gas turbines, steam turbines, reciprocating engines
- Hot working and casting tools and dies
- Aircraft & space vehicles
- Nuclear and chemical industries

- Iron based alloys:
  - 32% to 67% Fe, 15% to 22% Cr and 9% to 38% Ni.
  - common alloys: **Incoloy** series

- Cobalt based alloys:
  - 30% to 65% Co, 19% to 30% Cr and up to 35% Ni.
  - they retain their strength at high temp. but not as strong as Ni-base superalloys

- Nickel based alloys:
  - 38% to 76% Ni, up to 27% Cr and 20% Co.
  - are the most common superalloys
  - common alloys: **Hastelloy, Inconel, Nimonic, Rene and Astralloy** series
**Miscellaneous Nonferrous Alloys**

- **Cobalt**: similar in size, melting point and density to nickel.
- **Lead & alloys**: x-ray shields and storage batteries.
- **Tin**: a very thin coating on the inside of plain carbon steel cans (tin cans); this coating inhibits chemical reactions between the steel and the food products.

**Lead, tin and their alloys:**
- Both are mechanically soft and weak.
- Have low melting temperatures.
- Are quite resistant to many corrosion environments.
- And have recrystallization temperatures below room temperature.

**Miscellaneous Nonferrous Alloys**

- **Cobalt**: similar in size, melting point and density to nickel.
- Less susceptible to hot corrosion, but more susceptible to oxidation.
- Useful for low stress, long life at high temperature.

- **Tin**: a very thin coating on the inside of plain carbon steel cans (tin cans); this coating inhibits chemical reactions between the steel and the food products.

**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.

- **Ti Alloys**
  - Lower $\rho$: 4.5g/cm$^3$ vs 7.9 for steel.
  - Reactive at high T.
  - Space applic.

- **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, electronics, cars.

- **Noble metals**
  - Ag, Au, Pt.
  - Oxid./corr. resistant.

- **Refractory metals**
  - High melting T.
  - Nb, Mo, W, Ta.

**Zirconium alloys** are ductile and have other mechanical characteristics that are comparable to titanium alloys & austenitic stainless steels.

- Primary asset is their resistance to corrosion in a host of corrosive media, including superheated water.
- Zirconium is **transparent to thermal neutrons**, alloys used as cladding for uranium fuel in water-cooled nuclear reactors.
- In terms of cost, these alloys are also often the materials of choice for heat exchangers, reactor vessels, and piping systems for the chemical-processing and nuclear industries.

**Next Time**

Review for the Final