Outline

- Introduction
- Relative cost of materials
- Example
- Materials selection: Artificial hip joint materials
- Space Shuttle Thermal Protection System

Price and Availability

- Current Prices on the web:\n  - Short term trends: fluctuations due to \ldots/\ldots.
  - Long term trend: prices will increase as rich deposits are depleted.

- Materials require energy to process them:

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy to produce materials (GJ/ton)</th>
<th>Cost of energy used in processing materials ($/GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>237 (17)(^{(b)})</td>
<td>elect resistance 25</td>
</tr>
<tr>
<td>PET</td>
<td>103 (13)(^{(c)})</td>
<td>propane 11</td>
</tr>
<tr>
<td>Cu</td>
<td>97 (20)(^{(b)})</td>
<td>natural gas 9</td>
</tr>
<tr>
<td>steel</td>
<td>20(^{(d)})</td>
<td>Oil (~100$/barrel) 8</td>
</tr>
<tr>
<td>glass</td>
<td>13(^{(c)})</td>
<td></td>
</tr>
<tr>
<td>paper</td>
<td>9(^{(f)})</td>
<td></td>
</tr>
</tbody>
</table>

Energy using recycled material indicated in green.

Relative Cost of Materials

\[ C_m = \frac{\$}{kg} \] (\$/kg) \text{ref material}

- Reference material:
  - Rolled A36 plain carbon steel.
- Relative cost, $, fluctuates less over time than actual cost.

Detailed Study I: Strong, Light Torsion Members

- Maximize the Performance Index:
  \[ P = \frac{\tau_f^{2/3}}{\rho} \]

- Other factors:
  - require $\sigma_f > 300$MPa.
  - Rule out ceramics and glasses because $K_{ic}$ too small.
Strong, Light Torsion Members

- Numerical Data:

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (Mg/m$^3$)</th>
<th>$\tau_f$ (MPa)</th>
<th>$P$ (MPa$^{2/3}$/m$^3$/Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRE (vf = 0.65)</td>
<td>1.5</td>
<td>1140</td>
<td>73</td>
</tr>
<tr>
<td>GFRE (vf = 0.65)</td>
<td>2.0</td>
<td>1060</td>
<td>52</td>
</tr>
<tr>
<td>Al alloy (2024-T6)</td>
<td>2.8</td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>Ti alloy (Ti-6Al-4V)</td>
<td>4.4</td>
<td>525</td>
<td>15</td>
</tr>
<tr>
<td>4340 steel (oil quench &amp; temper)</td>
<td>7.8</td>
<td>780</td>
<td>11</td>
</tr>
</tbody>
</table>

Data from Table 6.6, Callister 6e.

- Lightest: Carbon Fiber Reinf. Epoxy (CFRE) member.
- Heaviest: 4340 steel

Strong, Low Cost Torsion Members

Considering (Cost/Mass)$^*\text{Mass} = \frac{C_m}{P}$

- Minimize Cost: Cost Index ~ M$^\text{S} \sim \frac{C_m}{P}$ (since M \sim 1/P)

- Numerical Data:

<table>
<thead>
<tr>
<th>Material</th>
<th>$P$ (MPa$^{2/3}$/m$^3$/Mg)</th>
<th>$C_m$</th>
<th>$\left(\frac{C_m}{P}\right)\times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRE (vf=0.65)</td>
<td>73</td>
<td>80</td>
<td>112</td>
</tr>
<tr>
<td>GFRE (vf=0.65)</td>
<td>52</td>
<td>40</td>
<td>76</td>
</tr>
<tr>
<td>Al alloy (2024-T6)</td>
<td>16</td>
<td>15</td>
<td>93</td>
</tr>
<tr>
<td>Ti alloy (Ti-6Al-4V)</td>
<td>15</td>
<td>110</td>
<td>748</td>
</tr>
<tr>
<td>4340 steel (oil quench &amp; temper)</td>
<td>11</td>
<td>5</td>
<td>46</td>
</tr>
</tbody>
</table>

Data from Table 6.7, Callister 6e.

- Lowest cost: 4340 steel (oil quench & temper)
- Need to consider machining, joining costs also.

Materials selection: Artificial hip joint materials

- bone is a natural anisotropic material
- hip \rightarrow ball and socket type joint
- friction
- large range of rotary motion

<table>
<thead>
<tr>
<th>Property</th>
<th>Parallel to Bone Axis</th>
<th>Perpendicular to Bone Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus, GPa (psi)</td>
<td>(2.48 \times 10^6)</td>
<td>(1.67 \times 10^6)</td>
</tr>
<tr>
<td>Ultimate strength, tension, MPa (ksi)</td>
<td>135</td>
<td>618</td>
</tr>
<tr>
<td>Ultimate strength, compression, MPa (ksi)</td>
<td>196</td>
<td>125</td>
</tr>
<tr>
<td>Elongation at fracture</td>
<td>3-4%</td>
<td></td>
</tr>
</tbody>
</table>

Table 23.13 Mechanical Characteristics of Human Long Bone Both Parallel and Perpendicular to the Bone Axis.

- Susceptible to fracture within the narrow region below the head
- Another problem is a disease when small lumps of bone form on the rubbing surfaces (Osteoarthritis) \rightarrow very painful
- need

![FIGURE 23.12 X-Rays of (a) a normal hip joint and (b) a fractured hip joint. The arrows in (b) show the two ends of the fracture line through the femoral neck.]
Materials selection: Artificial hip joint materials

What are the materials used for artificial hip joint?
What are the materials constraints for hip joint?

Factors for Implant Material Selection

**Biocompatibility**: minimum degree of rejection by body

**Corrosion**: warm aqueous solution + 1% NaCl, require low corrosion rate and minimum corrosion products.

**Mechanical**: Strength, stiffness, fatigue, fracture toughness.

  E.g for stem – 500 MPa < Yield and 650 MPa < Tensile strength, 8% < Elongation, Fatigue strength > 400 MPa for 10⁷ cycles (approx 10⁶ per year)

  Mechanical properties should not be very different from those of bones, otherwise deterioration will take place.

**Wear**: minimise

**Friction**: minimise

**Density**: low for lightweight

**Reliability**: consistent properties over time

**Cost**: reasonable

Materials selection: Artificial hip joint materials

- **Earlier design**: same material for stem and ball → Stainless Steel
- **Recently**: different materials other than SS.

  Old inactive person

  The most biocompatible (MP35N = 35% Co - 35% Ni - 20% Cr - 10% Mo)

  **Recent development**: ceramic for the ball (Al₂O₃ → harder and more wear resistant)

  **Acetabular cup** - usually UHMWPE (inert, excellent wear resistance and low friction with the ball materials)

  **Fixation** is with PMMA cement (not great because it is brittle. Using porous material where bone tissues grow is better)

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**Table 23.4** Mechanical and Corrosion Characteristics of Three Metal Alloys That Are Commonly Used for the Femoral Stem Component of the Prosthetic Hip

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Fatigue Strength or Limit (MPa)</th>
<th>Corrosion Rate (mpy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>316L Stainless steel (cold worked)</td>
<td>196</td>
<td>300</td>
<td>875</td>
<td>12</td>
<td>383</td>
<td>0.001 – 0.002</td>
</tr>
<tr>
<td>MP35N (hot forged)</td>
<td>230</td>
<td>1000</td>
<td>1200</td>
<td>13</td>
<td>500</td>
<td>0.0012 – 0.002</td>
</tr>
<tr>
<td>Ti-6Al-4V (hot forged)</td>
<td>120</td>
<td>950</td>
<td>1675</td>
<td>13</td>
<td>580</td>
<td>0.007 – 0.04</td>
</tr>
</tbody>
</table>

* mpy means miles per year, or 0.001 in./yr
1. Maintain the temperature on the inner airframe below certain temp. [e.g., 175°C] for a maximum outer surface temperature of 1465°C.
2. Remain usable for 100 missions, with a maximum turnaround time of 160 h.
3. Provide and maintain an aerodynamically smooth outer surface.
4. Be constructed of …………. materials.
5. Withstand temperature extremes between -110°C and 1465°C.
6. Be resistant to severe thermal gradients and rapid temperature changes.
7. Be able to withstand stresses and vibrations that are experienced during launch, as well as thermally induced stresses imposed during temperature changes.
8. Experience a minimum absorption of moisture and other contaminants during storage between missions.
9. Be made to adhere to the airframe that is constructed of an aluminum alloy.

Space Shuttle Thermal Protection System

- **FRSI**, felt reusable surface insulation;
- **AFRSI**, advanced flexible reusable surface insulation;
- **LRSI**, low-temperature reusable surface insulation;
- **HRSI**, high-temperature reusable surface insulation;
- **RCC**, reinforced carbon–carbon composite

**Is there a single material which satisfies all these requirements?**

**Table 23.5** Thermal Protection Systems Employed on the Space Shuttle Orbiter

<table>
<thead>
<tr>
<th>Material Category</th>
<th>Max. Operating Temperature, °C</th>
<th>Min. Operating Temperature, °C</th>
<th>Material Composition</th>
<th>Application Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felt reusable surface insulation (FRSI)</td>
<td>-130 (-200)</td>
<td>-30 (-50)</td>
<td>Nylon felt, silicone rubber coating</td>
<td>Wing upper surface, upper nose, fore bay doors</td>
</tr>
<tr>
<td>Advanced flexible reusable surface insulation (AFRSI)</td>
<td>-130 (-200)</td>
<td>815 (1500)</td>
<td>Quartz heat-resistant fibers between ceramic parts</td>
<td>Upper surface regions</td>
</tr>
<tr>
<td>Low-temperature reusable surface insulation (LRSI)</td>
<td>-130 (-200)</td>
<td>650 (1200)</td>
<td>Silica tiles, boron ceramics</td>
<td>Upper wing surfaces, tail surfaces, upper vehicle sides</td>
</tr>
<tr>
<td>High-temperature reusable insulation (HRSI)</td>
<td>-130 (-200)</td>
<td>1260 (2300)</td>
<td>Silica tiles, boron ceramics</td>
<td>Lower surfaces and sides, tail leading and trailing edges</td>
</tr>
<tr>
<td>Reinforced carbon–carbon (RCC)</td>
<td>No lower limit identified</td>
<td>1600 (2900)</td>
<td>Phenolic carbon-carbon coating with SiC</td>
<td>Nose cap and wing leading edges</td>
</tr>
</tbody>
</table>
Space Shuttle Thermal Protection System

- For regions that are exposed to higher temperature (400 to 1260°C);
- ceramic tiles (more complex) are used because ceramics are thermal insulators and can withstand high temperature.
- 24,300 tiles (70% of the exterior area)
- each tile is different

**FIGURE 23.17** Photograph showing the installation of thermal protection ceramic tiles on the Space Shuttle Orbiter.

**FIGURE 23.18** SEM micrograph of a Space Shuttle Orbiter ceramic tile showing silica fibers after sintering.

**Next time:**

*Materials Codes*