Announcements

• Quiz in lecture on Wednesday
  – Chapter 18 Electrical Properties
  – Chapter 19 Thermal Properties
  – Also an anonymous end-of-term survey

• Also on Wednesday
  – Hand out a study guide for the final exam
Polymers

• Polymers
  – 14.7, 14.9
  – 15.1 – 15.5
  – Jones, Ch. 8
  – Lecture notes
2. Creep (50 point(s)) A major design consideration is taking into account creep. Consider the following material options commonly used for microelectronics. For each indicate whether creep is a design concern for the material at the temperature of interest. In each case, how big of a concern is it and why?

- For the board - Option 1 is standard FR4 board with a polymer-glass composite and Cu. Option 2 is a ceramic with patterned Al and Cu conductors.

- For the solders - Option 1 is eutectic Pb-Sn solder (Callister Fig. 9.9). Option 2 is eutectic Au-Sn (80wt% Au, Callister Fig. 9.36).
3. Minimize Creep (40 point(s)) Consider that the company is constrained to using the materials identified in the previous problem as having the biggest issues with creep. Based on your knowledge of steady state creep behavior, identify two design changes that could be implemented to minimize the creep strain rate (Besides changing materials). Discuss how these changes could be implemented.

\[
\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)
\]

- strain rate
- material const. 
- applied stress
- stress exponent (material parameter)
- activation energy for creep (material parameter)
Chapter 19: Thermal Properties

ISSUES TO ADDRESS...

• How does a material respond to heat?

• How do we define and measure...
  -- heat capacity
  -- coefficient of thermal expansion
  -- thermal conductivity
  -- thermal shock resistance

• How do ceramics, metals, and polymers rank?
Heat Capacity

- General: The ability of a material to absorb heat.
- Quantitative: The energy required to increase the temperature of the material.

\[ C = \frac{dQ}{dT} \]

- Two ways to measure heat capacity:
  \[ C_p \]: Heat capacity at constant pressure.
  \[ C_v \]: Heat capacity at constant volume.

\[ C_p > C_v \]

- Specific heat has typical units of \( \frac{J}{kg \cdot K} \)
Heat Capacity vs $T$

- Heat capacity...
  -- increases with temperature
  -- reaches a limiting value of $3R$

- Atomic view:
  -- Energy is stored as atomic vibrations.
  -- As $T$ goes up, so does the avg. energy of atomic vibr.

\[ C_v = \text{constant} \]

\[ C_v = A T^3 \]

Debye temperature (usually less than $T_{room}$)

Adapted from Fig. 19.2, Callister 7e.

Gas constant $= 8.31$ J/mol-K
Energy Storage

How is the energy stored?

**Phonons** – thermal waves - vibrational modes

Adapted from Fig. 19.1, *Callister 7e.*

- Normal lattice positions for atoms
- Positions displaced because of vibrations
Energy Storage

• Other small contributions to energy storage
  – Electron energy levels
    • Dominate for ceramics & plastics
  – Energy storage in vibrational modes

Adapted from Fig. 19.3, Callister 7e.
# Heat Capacity: Comparison

The heat capacity, $c_p$, is a measure of the amount of thermal energy required to raise the temperature of a material by one degree Kelvin. It is typically expressed in J/kg-K for substances like polymers and J/mol-K for substances like metals.

<table>
<thead>
<tr>
<th>Material</th>
<th>$c_p$ (J/kg-K)</th>
<th>$c_p$ (J/mol-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polymers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1925</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>1850</td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>1170</td>
<td></td>
</tr>
<tr>
<td>Teflon</td>
<td>1050</td>
<td></td>
</tr>
<tr>
<td><strong>Ceramics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesia (MgO)</td>
<td>940</td>
<td></td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>775</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>486</td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>128</td>
<td></td>
</tr>
</tbody>
</table>

- **Why is $c_p$ significantly larger for polymers?**
  1. Less dense
  2. More vibrational modes

Selected values from Table 19.1, *Callister 7e.*

Chapter 19 - 10
Thermal Expansion

- Materials change size when heating.

\[
\frac{L_{\text{final}} - L_{\text{initial}}}{L_{\text{initial}}} = \alpha(T_{\text{final}} - T_{\text{initial}})
\]

\(\alpha\) coefficient of thermal expansion (1/K or 1/°C)

- Atomic view: Mean bond length increases with \(T\).

Adapted from Fig. 19.3(a), Callister 7e.
(Fig. 19.3(a) adapted from R.M. Rose, L.A. Shepard, and J. Wulff, The Structure and Properties of Materials, Vol. 4, Electronic Properties, John Wiley and Sons, Inc., 1966.)

bond energy vs bond length curve is “asymmetric”
# Thermal Expansion: Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha_t (10^{-6}/K)$ at room $T$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polymers</strong></td>
<td></td>
</tr>
<tr>
<td>Polypropylene</td>
<td>145-180</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>106-198</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>90-150</td>
</tr>
<tr>
<td>Teflon</td>
<td>126-216</td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>23.6</td>
</tr>
<tr>
<td>Steel</td>
<td>12</td>
</tr>
<tr>
<td>Tungsten</td>
<td>4.5</td>
</tr>
<tr>
<td>Gold</td>
<td>14.2</td>
</tr>
<tr>
<td><strong>Ceramics</strong></td>
<td></td>
</tr>
<tr>
<td>Magnesia (MgO)</td>
<td>13.5</td>
</tr>
<tr>
<td>Alumina (Al$_2$O$_3$)</td>
<td>7.6</td>
</tr>
<tr>
<td>Soda-lime glass</td>
<td>9</td>
</tr>
<tr>
<td>Silica (cryst. SiO$_2$)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- **Q:** Why does $\alpha$ generally decrease with increasing bond energy?

Selected values from Table 19.1, *Callister 7e.*
**Thermal Expansion: Example**

Ex: A copper wire 15 m long is cooled from 40 to -9°C. How much change in length will it experience?

- **Answer:** For Cu \( \alpha_\ell = 16.5 \times 10^{-6} \ (°C)^{-1} \)

  rearranging Eqn 19.3b

  \[ \Delta \ell = \alpha_\ell \ell_0 \Delta T = [16.5 \times 10^{-6} (1/°C)](15 \text{ m})(40°C - (-9°C)) \]

  \[ \Delta \ell = 0.012 \text{ m} \]

  \[ \Delta \ell = -0.012 \text{ m} \]
Chapter 19 - 14

Thermal Conductivity

• General: The ability of a material to transfer heat.
• Quantitative:
  \[ q = -k \frac{dT}{dx} \]
  - Heat flux (J/m²-s)
  - Thermal conductivity (J/m-K-s)

  \[ \text{Fourier’s Law} \]

  \[ \frac{w}{m \cdot K} \]

• Atomic view: Atomic vibrations in hotter region carry energy (vibrations) to cooler regions.

T₁ > T₂

x₁

x₂
### Thermal Conductivity: Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>k (W/m-K)</th>
<th>Energy Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>247</td>
<td>By vibration of atoms and motion of electrons</td>
</tr>
<tr>
<td>Steel</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>315</td>
<td></td>
</tr>
<tr>
<td><strong>Ceramics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesia (MgO)</td>
<td>38</td>
<td>By vibration of atoms</td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Soda-lime glass</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Silica (cryst. SiO₂)</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td><strong>Polymers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.12</td>
<td>By vibration/rotation of chain molecules</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.46-0.50</td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Teflon</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>

Selected values from Table 19.1, *Callister 7e.*
Thermal Stress

- Occurs due to:
  -- uneven heating/cooling
  -- mismatch in thermal expansion.

- Example Problem 19.1, *Callister 7e*.
  -- A brass rod is stress-free at room temperature (20°C).
  -- It is heated up, but prevented from lengthening.
  -- At what $T$ does the stress reach -172 MPa?

\[
\frac{\Delta L}{L_{\text{room}}} = \varepsilon_{\text{thermal}} = \alpha (T - T_{\text{room}})
\]

\[
\sigma = E(-\varepsilon_{\text{thermal}}) = -E\alpha(T - T_{\text{room}})
\]

Answer: 106°C

- Compressive $\sigma$ keeps $\Delta L = 0$ -172 MPa

---

Chapter 19 - 16
Thermal Protection System

• Application:
  Space Shuttle Orbiter

• Silica tiles (400-1260°C):
  --large scale application

~90% porosity!
Si fibers bonded to one another during heat treatment.

Fig. 19.2W, Callister 6e. (Fig. 19.2W adapted from L.J. Korb, C.A. Morant, R.M. Calland, and C.S. Thatcher, "The Shuttle Orbiter Thermal Protection System", Ceramic Bulletin, No. 11, Nov. 1981, p. 1189.)

Fig. 19.3W, Callister 5e. (Fig. 19.3W courtesy the National Aeronautics and Space Administration.)

Fig. 19.4W, Callister 5e. (Fig. 219.4W courtesy Lockheed Aerospace Ceramics Systems, Sunnyvale, CA.)
Summary

• A material responds to heat by:
  -- increased vibrational energy
  -- redistribution of this energy to achieve thermal equil.

• Heat capacity:
  -- energy required to increase a unit mass by a unit $T$.
  -- polymers have the largest values.

• Coefficient of thermal expansion:
  -- the stress-free strain induced by heating by a unit $T$.
  -- polymers have the largest values.

• Thermal conductivity:
  -- the ability of a material to transfer heat.
  -- metals have the largest values.