Manufacturing Process Homeworks 2011

1. Make an order of magnitude estimate of the minimum energy-primary fuels, assume all processes are electric (not asking for exergy) required per unit mass (in kJ/kg) to: 1) machine (plastically deform), 2) melt, and 3) vaporize aluminum and steel. You may use the values given in Table 1 below, as well as other information given in the class handouts.

<table>
<thead>
<tr>
<th></th>
<th>Y (MPa)</th>
<th>ρ (kg/m³)</th>
<th>C (kJ/kg·K)</th>
<th>Tm (K)</th>
<th>Tv (K)</th>
<th>Hm (kJ/kg)</th>
<th>Hv (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>2000</td>
<td>8000</td>
<td>0.5</td>
<td>1773</td>
<td>~3134</td>
<td>270</td>
<td>6259</td>
</tr>
<tr>
<td>Aluminum</td>
<td>330</td>
<td>2700</td>
<td>0.9</td>
<td>933</td>
<td>~2773</td>
<td>400</td>
<td>10900</td>
</tr>
</tbody>
</table>

2. Estimate actual energy usage for machining, casting and a vapor phase processes compared to these theoretical values. What do you think was left out?

3. Compare these values with the values given by Ashby in Figure 6.12 on page 120 of his book.

4. Compare the values you obtained in question 2, to the values given in Figure 9 in Ch 6 by Gutowski & Sekulic (class reading for manufacturing)

5. Do problem 1 above for the minimum work (exergy) for aluminum.
FIGURE 6.12  Approximate processing energies for materials.
Manufacturing Process Homeworks 2011

1. Make an order of magnitude estimate of the minimum energy-primary fuels, assume all processes are electric (not asking for exergy) required per unit mass (in kJ/kg) to: 1) machine (plastically deform), 2) melt, and 3) vaporize aluminum and steel. You may use the values given in Table 1 below, as well as other information given in the class handouts.

<table>
<thead>
<tr>
<th></th>
<th>Y (MPa)</th>
<th>ρ (kg/m³)</th>
<th>C (kJ/kg·K)</th>
<th>Tm (K)</th>
<th>Tv (K)</th>
<th>*Hm (kJ/kg)</th>
<th>*Hv (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>2000</td>
<td>8000</td>
<td>0.5</td>
<td>1773</td>
<td>~3134</td>
<td>270</td>
<td>6259</td>
</tr>
<tr>
<td>Aluminum</td>
<td>330</td>
<td>2700</td>
<td>0.9</td>
<td>933</td>
<td>~2773</td>
<td>400</td>
<td>10900</td>
</tr>
</tbody>
</table>

Table 1. Selected Approximate Material Properties

Answer for aluminum

1. Machining, use the "specific energy" values given in class (slide 21) for aluminum alloys (pure aluminum will be on the softer side).

\[ U_s = 0.4 \text{ Ws/mm}^3 = 148 \text{ kJ/kg} \]
\[ U_f = 1.1 \times 407 \text{ kJ/kg} \]

2. Melting

\[ U_m = 0.9(933 - 293) + 400 = 976 \text{ kJ/kg} \]

3. Vaporization

\[ U_v = U_m + \int C \, dT + 10,900 \]

If we assume C (specific heat of the liquid) \( \sim C \) (solid), then \( U_v \sim 13,500 \text{ kJ/kg} \).

So the minimum energy increases by about an order of magnitude each time when we go from machining, to melting, to vaporization.
2. Estimate actual energy usage for machining, casting and a vapor phase processes compared to these theoretical values. What do you think was left out?

Look for inefficiencies in the physics, method of delivery, aux equip, utilities

3. Compare these values with the values given by Ashby in Figure 6.12 on page 120 of his book.

4. Compare the values you obtained in question 2, to the values given in Figure 9 in Ch 6 by Gutowski & Sekulic (class reading for manufacturing)

These are measurements of electricity

5. Do problem 1 above for the minimum work (exergy) for aluminum.

compare 1st law analysis w/ 2nd law (exergy)

ex. energy to raise temp of block

\[ Q_{\text{min}} = c \Delta T = \frac{976 \text{kJ}}{\text{kg}} \]

exergy (see Ch 6)

\[ W_{\text{min}} = c \Delta T - T_0 \ln \frac{T}{T_0} = \frac{545 \text{kJ}}{\text{kg}} \]

Explanation: Use heat pump

To ≠ zero Kelvin

\( T \) environment has heat

(thermal energy - atomic motion)

(but no exergy)

\[ \text{min work} = \text{reversible work} \]

(heat pump) (heat engine)
Machining Processes (2011)

Power

\[ \text{rate} \]

\[ \text{physical work + friction} = U_s \quad \text{(slide #15 Mfg.)} \]

\[ \text{depends upon machine} \quad \text{(slide #16 Mfg.)} \]

\[ \frac{E}{V} = \frac{P_{aux} + U_s \times \text{MRR}}{\text{MRR}} \]

Lots of variations!

\[ \text{depends upon MRR} \]

Physical Parts:

Aluminum:

\[ U_s = 0.4 \text{ to } 1.1 \quad \frac{J}{\text{mm}^3} \times \left(\frac{10 \text{ mm}}{\text{cm}}\right)^3 \times \frac{1}{2.7 \text{ g}} \quad \text{(slide #15 Mfg., Tech.)} \]

\[ = 0.15 \text{ to } 0.41 \quad \frac{\text{MJ}}{\text{kg}} \]

Width \times 3

\[ = 0.45 \text{ to } 1.2 \quad \frac{\text{MJ}}{\text{kg}} \]

Aux Equip:

Power ratio:

physical: aux

manual \quad CNC \quad production

1:0 \quad 1:2 \quad 1:10

Power

rate

Range:

\[ 0.45 \frac{\text{MJ}}{\text{kg}} \]

\[ 1.2 \text{ to } 12.0 = 13.2 \frac{\text{MJ}}{\text{kg}} \]

Soft aluminum, manual machine

Hard alloy, production machine, non-max MRR
Casting Processes

From #1 \[ Um = 1 \frac{MJ}{kg} \] (both alu and iron)

need to include: 1. Runners, risers & Scrap
(depending on part and technology, ball park number \( \approx 2x \))

2. Furnace efficiency
(depending on technology and operating conditions, ball park number \( \approx 2x \))

3. For electric furnaces, loses at utility \( 3x \)

4. All other activities at the foundry, pouring, shakeout, mold making, finishing... "Balance of the foundry" \( \approx 2x \)

This results in a range from \[ 8 \text{ to } 24 \frac{MJ}{kg} \]

Vapor Phase Processes

ex. PVD-sputtering

process is inefficient because it coats the inside of the chamber as well as the target \( \approx \) depends on geometry. A crude lowball est. for alu

\[ 13.5 \times 2 \times 2 \times 3 = 160 \frac{MJ}{kg} \]
Gibotacei & Sekulic (Ch 6)

Machining
1 - 10 MJ/kg electricity
3 - 30 MJ/kg primary energy
1.3 - 8.8 (machining, milling, grinding)

Casting
Only give melts

Electric melters ~ 1 - 3 MJ/kg (elec)
x3 ⇒ 3 - 9 MJ/kg (pri)

double for foundry 6 - 18 MJ/kg

Note 81K code for this activity
National averages are higher
above range agrees well.
11.6 - 29* (sand casting, iron casting, etc, cupola melt, dc casting)

Neenah Foundry

Vapor phase sputtering 2 to 200 GJ/kg electricity

Wet pond ray ~ 20 GJ/kg (electrical)
x3 ⇒ 60 GJ/kg (primary)

or 6,000 to 600,000 MJ/kg!

recall

\[ P = P_{aux} + k \cdot V \] (or W)

lots of variation

\[ \frac{E}{m} \quad \Delta \quad \frac{W}{m} \]

(good thing ray is usually small contributor to energy)
<table>
<thead>
<tr>
<th></th>
<th>Machining</th>
<th>Casting</th>
<th>Vapor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum energy</td>
<td>0.5 (alu)</td>
<td>1 (alu &amp; iron, does not include heating above Tm)</td>
<td>14 (alu)</td>
</tr>
<tr>
<td>(#1 see attached)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical reasoning</td>
<td>0.5 – 13.0</td>
<td>8 – 24</td>
<td>160</td>
</tr>
<tr>
<td>(#2 see attached)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ch. 6 by Gutowski &amp; Sekulic Mostly from measurements (#4 see attached)</td>
<td>3 – 30</td>
<td>6 – 18</td>
<td>6,000 – 600,000 (sputtering)</td>
</tr>
<tr>
<td>LCA slide # From paper by N. Duque Ciceri Mostly based on the literature</td>
<td>1 – 9</td>
<td>12 – 29</td>
<td></td>
</tr>
<tr>
<td>Ashby’s book Fig 6.12 page 120 (#3 see attached)</td>
<td>1 – 4</td>
<td>2 – 7</td>
<td>5 - 40</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td><strong>0.5 – 30</strong></td>
<td><strong>2 – 29</strong></td>
<td><strong>Too much variation to list</strong></td>
</tr>
</tbody>
</table>

These process energy intensity values vary by about 2 orders of magnitude or more. This variation is due to variation in operating conditions, in particular process rate, alternative process configurations and technologies, and equipment size among other factors.
Heat Pump

\[ T \]
\[ S_{Q_i} \]
\[ S_W \rightarrow \]
\[ S_{Q_0} \]
\[ T_0 \]

\( T_0 \neq \) zero kelvin
\( \therefore \) it has thermal energy
( but zero energy)

**1st law**

\[ S_{Q_0} + S_W = S_{Q_i} \]

apply to heat pump

\[ a \quad S_W = S_{Q_i} - S_{Q_0} \]

\[ SW = S_{Q_i}(1 - \frac{T_0}{T}) \]

**recall**

\[ \frac{S_{Q_0}}{S_{Q_i}} = \frac{T_0}{T_i} \]

now \( S_{Q_i} = C dT \)

(applied to block)

\[ \Delta W_{\text{min}} = (1 - \frac{T_0}{T}) \quad C dT \]

Energy approach is easier

\[ B_w = W \]

\[ \uparrow B_i = Q_{in} (1 - \frac{T_0}{T}) \]

\[ \uparrow B_o = 0 \]

\[ T_0 \]

Balance

\[ dW = S_{Q_i} (1 - \frac{T_0}{T}) \quad + dB_{\text{lost}} \]

\[ dW_{\text{min}} = C (1 - \frac{T_0}{T}) dT \]