Energy & Exergy Efficiency of Manufacturing Processes

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Mfg Processes in Thermodynamic Framework

1. Machining
2. Grinding
3. Casting
4. Injection Molding
5. Abrasive Waterjet
6. EDM
7. Laser DMD
8. CVD
9. Sputtering
10. Thermal Oxidation

Figure from Gyftopoulos & Berreta
Issues

1. Resource Accounting
   • Work, heat, materials transformations

2. Process Improvement
   • Minimum work or reversible work: exergy
Balances for Mfg Process

**Mass**

\[
\frac{dm_{MF}}{dt} = (\sum_{i=1}^{\infty} \dot{N}_{i,in}^{MF} M_i^{MF}) - (\sum_{i=1}^{\infty} \dot{N}_{i,out}^{MF} M_i^{MF})
\]

**Energy**

\[
\frac{dE_{MF}}{dt} = \sum_i \dot{Q}_{ECMF}^{MF} - \dot{Q}_0^{MF} \rightarrow + \dot{W}^{MF}_{ECMF}
\]

\[
+ \dot{H}_{MF}^{mat} - \dot{H}_{MF}^{prod} - \dot{H}_{MF}^{res}
\]

**Entropy**

\[
\frac{dS_{MF}}{dt} = \sum_i \frac{\dot{Q}_{ECMF}^{MF} - \dot{Q}_0^{MF} \rightarrow}{T_i} + \dot{S}_{MF}^{mat} - \dot{S}_{MF}^{prod} - \dot{S}_{MF}^{res} + \dot{S}_{irr,MF}
\]

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Work Rate for Mfg Process in Steady State

\[
\dot{W}_{ECMF}^{MF} = \left( (\dot{H}_{MF}^{prod} + \dot{H}_{MF}^{res}) - \dot{H}_{MF}^{mat} \right) - T_0 \left( (\dot{S}_{MF}^{prod} + \dot{S}_{MF}^{res}) - \dot{S}_{MF}^{mat} \right) - \sum_{i>0} \left( 1 - \frac{T_0}{T_i} \right) \dot{Q}_{ECMF}^{MF} + T_0 \dot{S}_{irr,MF}
\]

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Exergy and Work

\[ B = (H - T_o S) - (H - T_o S)_o \]

\[ \dot{W}_{ECMF}^{MF} = \left( (\dot{B}_{MF}^{prod} + \dot{B}_{MF}^{res}) - \dot{B}_{MF}^{mat} \right) \]

\[ - \sum_{i>0} \left( 1 - \frac{T_0}{T_i} \right) \dot{Q}_{ECMF}^{MF} + T_0 \dot{S}_{irr, MF} \]

Branham et al IEEE ISEE 2008

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Mfg Process Use of Electricity

1. Machining
2. Grinding
3. Casting
4. Injection Molding
5. Abrasive Waterjet
6. EDM
7. Laser DMD
8. CVD
9. Sputtering
10. Thermal Oxidation
Figure 24.2 The burning of a fuel-air mixture in the energy-conversion system provides the work needed to process the bulk-flow stream through the materials-processing system.
Energy Requirements at the Machine Tool

Energy Use Breakdown by Type

Production Machining Center

Automated Milling Machine

Electric Energy Intensity for Manufacturing Processes

\[ P = P_o + k_v \dot{V}_{\text{processed}} \]

\[ \frac{P}{V} = \frac{P_o}{\dot{V}} + k_v = \frac{E}{V} \]
The hydraulic machine would be even higher than the hybrid curve

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The hydraulic plot would be even higher than the hybrid curve

Source: [Thiriez]
Injection Molding Machines

Variable Pump Hydraulic Injection Molding Machines.

\[
\frac{P}{\dot{m}} = \frac{P_0}{\dot{m}} + k_m = \frac{E}{m}
\]

Does not account for the electric grid.

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Thermal Oxidation, $SiO_2$

![Graph showing energy consumption for growth of a 25-Å oxide layer as a function of equipment type (RTP vs vertical furnace), number of wafers processed per week, and total run time (production plus idle). The example shown is for 8-in. wafers.]

Ref: Murphy et al es&t 2003

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# Power Requirements

**TABLE 2. Average Number of Functions, Throughputs, and Power Requirements for a Hypothetical 0.13-μM Microprocessor Wafer Fab**

<table>
<thead>
<tr>
<th>unit operation</th>
<th>no. of functions</th>
<th>8-layer metal</th>
<th>6-layer metal</th>
<th>wafers/ run</th>
<th>wafers/ h</th>
<th>power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>implant</td>
<td>16</td>
<td>16</td>
<td>25</td>
<td>20</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>CVD</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>15</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>wafer clean</td>
<td>35</td>
<td>31</td>
<td>50</td>
<td>150</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>furnace</td>
<td>21</td>
<td>17</td>
<td>150</td>
<td>35</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>furnace (RTP)</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>10</td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>photo (stepper)</td>
<td>27</td>
<td>23</td>
<td>1</td>
<td>60</td>
<td></td>
<td>115</td>
</tr>
<tr>
<td>photo (coater)</td>
<td>27</td>
<td>23</td>
<td>1</td>
<td>60</td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>etch (pattern)</td>
<td>24</td>
<td>20</td>
<td>1</td>
<td>35</td>
<td></td>
<td>135</td>
</tr>
<tr>
<td>etch (ash)</td>
<td>27</td>
<td>23</td>
<td>1</td>
<td>20</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>metallization</td>
<td>11</td>
<td>9</td>
<td>1</td>
<td>25</td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>CMP</td>
<td>18</td>
<td>14</td>
<td>1</td>
<td>25</td>
<td></td>
<td>29</td>
</tr>
</tbody>
</table>

Ref: Murphy et al  
es&t 2003

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<table>
<thead>
<tr>
<th>Process Name</th>
<th>Power Required</th>
<th>Process Rate</th>
<th>Electricity Required</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kW</td>
<td>cm$^3$/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Molding</td>
<td>10.76 - 71.40</td>
<td>3.76 - 50.45</td>
<td>of polymer processed</td>
<td>1.75E+03 - 3.41E+03</td>
</tr>
<tr>
<td>Machining</td>
<td>2.80 - 194.80</td>
<td>0.35 - 20.00</td>
<td>of material removed</td>
<td>3.50E+03 - 1.87E+05</td>
</tr>
<tr>
<td>Finish Machining</td>
<td>9.59</td>
<td>2.05E-03</td>
<td>of material removed</td>
<td>4.68E+06</td>
</tr>
<tr>
<td>CVD</td>
<td>14.78 - 25.00</td>
<td>6.54E-05 - 3.24E-03</td>
<td>of material deposited on wafer area</td>
<td>4.63E+06 - 2.44E+08</td>
</tr>
<tr>
<td>Sputtering</td>
<td>5.04 - 19.50</td>
<td>1.05E-05 - 6.70E-04</td>
<td>of material deposited on wafer area</td>
<td>7.52E+06 - 6.45E+08</td>
</tr>
<tr>
<td>Grindng</td>
<td>7.50 - 0.03</td>
<td>1.66E-02 - 2.85E-02</td>
<td>of material removed</td>
<td>6.92E+04 - 3.08E+05</td>
</tr>
<tr>
<td>Waterjet</td>
<td>8.16 - 16.00</td>
<td>5.15E-03 - 8.01E-02</td>
<td>of material removed</td>
<td>2.06E+05 - 3.66E+06</td>
</tr>
<tr>
<td>Wire EDM</td>
<td>6.60 - 14.25</td>
<td>2.23E-03 - 2.71E-03</td>
<td>of material removed</td>
<td>2.44E+06 - 6.39E+06</td>
</tr>
<tr>
<td>Drill EDM</td>
<td>2.63</td>
<td>1.70E-07</td>
<td>of material removed</td>
<td>1.54E+10</td>
</tr>
<tr>
<td>Laser DMD</td>
<td>80.00</td>
<td>1.28E-03</td>
<td>of material removed</td>
<td>6.24E+07</td>
</tr>
<tr>
<td>Thermal Oxidation</td>
<td>21.00 - 48.00</td>
<td>4.36E-07 - 8.18E-07</td>
<td>of material deposited on wafer area</td>
<td>2.57E+10 - 1.10E+11</td>
</tr>
</tbody>
</table>

References:
- [Thiriez 2006]
- [Wolf & Tauber 1986] & [Holland Interview]
- [Sodick], [Kalpakjian & Schmid 2001], & [AccuteX 2005]
- [Morrow, Qi & Skerlos 2004]
- [Morrow, Qi & Skerlos 2004]
- [Murphy et al. 2003]
In General, over many manufacturing processes,

Idle Power

\[ 5kW \leq P_o \leq 50kW \]

and

Material Process Rates

\[ 10^{-7} \text{ cm}^3/\text{sec} \leq \dot{V} \leq 1 \text{ cm}^3/\text{sec} \]
Specific Energy Requirements J/cm³ for Various Mfg Processes

Electricity Requirements [J/cm³]

Process Rate [cm³/s]

- Injection Molding
- CVD
- Abrasive Waterjet
- Laser DMD
- Machining
- Sputtering
- Wire EDM
- Finish Machining
- Grinding
- Drill EDM
- Upper Bound
- Lower Bound

Gutowski et al., ISEE 2007

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Specific Energy Requirements J/cm³ for Various Mfg Processes

Gutowski et al., ISEE 2007
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- Injection Molding
- CVD
- Abrasive Waterjet
- Laser DMD
- Machining
- Sputtering
- Wire EDM
- Oxidation
- Finish Machining
- Grinding
- Drill EDM
- Upper Bound

Upper Bound

Lower Bound

Electricity Requirements [J/cm³]

Process Rate [cm³/s]

8 orders of magnitude
Keep in Mind

• This is intensity not total used
• This is at the device
  – loses at energy conversion not included
  – investment into materials not included
  – infrastructure not included
• Suggestive of efficiency
Why are these energy intensities so high?

• stable and declining energy prices
• demand for small devices
• vapor phase processes with slow deposition rates
• efficiency used to enhance performance
• nevertheless, the trajectory of individual processes is toward faster rates and lower energy intensities
All Electric Vs Hydraulic Injection Molding Machines

Source: [Thiriez 2006]
Exergy Analysis including Chemical Composition

\[ B = (H - T_o S) - (H - T_o S)_o \]

- \( B = B^{ph} + B^{ch} \)
- \( B^{ph}(T=T_o, \ P=P_o) = 0 \)  
  \( \text{– this is the “restricted dead state”} \)
- when \( B = B^{ph} = 0 \), and
- \( B^{ch}(\mu^* = \mu_o) = 0 \)  
  \( \text{– this is the “dead state”} \)
Work Rate for Mfg Process

\[
\dot{W}^{MF\leftarrow ECMF} = ((\dot{B}_{MF}^{prod} + \dot{B}_{MF}^{res}) - \dot{B}_{MF}^{mat})^{ph} \\
+ \left( \sum_{i=1}^{n} b_{i}^{ch} \dot{N}_{i} \right)_{MF}^{prod} + \left( \sum_{i=1}^{n} b_{i}^{ch} \dot{N}_{i} \right)_{MF}^{res} - \\
\left( \sum_{i=1}^{n} b_{i}^{ch} \dot{N}_{i} \right)_{MF}^{mat} - \sum_{i>0}^{n} \left( 1 - \frac{T_{0}}{T_{i}} \right) \dot{Q}_{ECMF}^{MF} + T_{0} \dot{S}_{irr, MF}
\]

Here all chemical exergy terms \( (b^{ch}) \) are at \( T_o, P_o \)

Branham et al IEEE ISEE 2008

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Definition of Exergy “B”

“Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above mentioned components of nature” [Szargut et al 1988].

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Exergy

System State

Maximum work obtainable between System and Reference States.

Reference State

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Exergy

System State

Reference State

Maximum work obtainable between System and Reference States; or minimum work needed to raise System from the reference state to the System State

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Chemical Properties referenced to the “environment”

$T_0 = 298.2$ K,

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$P_0 = 101.3$ kPa

Crust

Oceans

Atmosphere
Exergy Reference System

- pure metal, element
- oxides, sulfides...
- crustal component
- earth’s crust (ground state)

chemical reactions

extraction

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Example: making pure iron from the crust

Fe (c = 1)  
Fe₂O₃ (c = 1)  
Fe₂O₃ (c = 1.3 x 10⁻³)  

376.4 kJ/mole  
16.5 kJ/mole  
0 kJ/mole (ground)

reduction

extraction

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Exergy Reference System

- Aluminum (c=1) 888.4 kJ/mole
- $\text{Al}_2\text{O}_3$ (c=1) 200.4 kJ/mole
- $\text{Al}_2\text{SiO}_5$ (c=1) 15.4 kJ/mole
- $\text{Al}_2\text{SiO}_5$ (c = $2 \times 10^{-3}$) 0 kJ/mole (ground)

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Exergy Accounting

\[ B_{in} - B_{out} = B_{lost} \]
**Chemical Reactions**

stoichiometric mass balance

\[ v_a R_a + v_b R_b + ... \rightarrow v_j \Pi_j + v_k \Pi_k + ... \]

exergy "balance"

\[ v_a b_{R_a} + v_b b_{R_b} + ... - v_j b_{\Pi_j} - v_k b_{\Pi_k} = B_{\text{lost}} \]

where exergy b is given in kJ/mole

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Efficiency Measures: 
Degree of Perfection

\[ \eta_p = \frac{B_{\text{useful output}}}{B_{\text{in}}} \]

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Batch Induction Melter Inputs and Outputs
Ductile Iron – Batch Electric Induction Exergy Analysis

Metallic Input Materials and Alloys
1024 kg

Input Electricity
5,393 MJ

Natural Gas Preheater
0.025 kg

Ductile Iron Melt
1000 kg

Slag
40 kg

Dust
0.26 kg

Boundaries are drawn around the entire facility so that all components are at standard pressure and temperature

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# Batch Induction Melter Exergy Analysis

## Ductile Iron Batch Electric Induction Melting

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount (kg)</th>
<th>Weight Percent</th>
<th>Standard Chemical Exergy (MJ/kg)</th>
<th>Exergy (MJ)</th>
<th>Percent Total Exergy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel Scrap</td>
<td>439</td>
<td>42.85%</td>
<td>6.89</td>
<td>3022.25</td>
<td>15.39%</td>
</tr>
<tr>
<td>Pig Iron</td>
<td>1.6</td>
<td>0.16%</td>
<td>8.18</td>
<td>13.43</td>
<td>0.07%</td>
</tr>
<tr>
<td>Ductile Iron Remelt</td>
<td>535</td>
<td>52.25%</td>
<td>8.44</td>
<td>4513.98</td>
<td>22.99%</td>
</tr>
<tr>
<td>65% Silicon Carbide Briquettes</td>
<td>4.3</td>
<td>0.42%</td>
<td>31.73</td>
<td>137.62</td>
<td>0.70%</td>
</tr>
<tr>
<td>75% Ferrosilicon</td>
<td>3.0</td>
<td>0.29%</td>
<td>24.51</td>
<td>72.46</td>
<td>0.37%</td>
</tr>
<tr>
<td>5% MgFeSi</td>
<td>14.8</td>
<td>1.44%</td>
<td>19.09</td>
<td>282.30</td>
<td>1.44%</td>
</tr>
<tr>
<td>Copper</td>
<td>1.7</td>
<td>0.17%</td>
<td>2.11</td>
<td>3.69</td>
<td>0.02%</td>
</tr>
<tr>
<td>Tin</td>
<td>0.005</td>
<td>0.00%</td>
<td>0.01</td>
<td>5418.00</td>
<td>55.59%</td>
</tr>
<tr>
<td>62% Fe-Molybdenum</td>
<td>6.2</td>
<td>0.61%</td>
<td>7.28</td>
<td>45.35</td>
<td>0.23%</td>
</tr>
<tr>
<td>Carbon 9012</td>
<td>18</td>
<td>1.80%</td>
<td>34.16</td>
<td>628.45</td>
<td>3.20%</td>
</tr>
<tr>
<td>Natural Gas Preheater</td>
<td>0.02</td>
<td>0.00%</td>
<td>51.84</td>
<td>1.27</td>
<td>0.01%</td>
</tr>
<tr>
<td><strong>Total Inputs</strong></td>
<td>1024</td>
<td>100.00%</td>
<td>14138.83</td>
<td>100.00%</td>
<td></td>
</tr>
</tbody>
</table>

| **Output Materials**            |             |                |                                 |             |                      |
| Ductile Iron Melt               | 1000.2      | 96.69%         | 8.44                            | 8436.45     | 99.29%               |
| Slag                            | 33.9        | 3.28%          | 1.14                            | 60.05       | 0.71%                |
| Dust                            | 0.3         | 0.02%          | 0.26                            | 0.07        | 0.00%                |
| **Total Outputs**               | 1034        | 100.00%        | 8497                            | 100.00%     |                      |

**Mass Difference**              | -1.05%      |                |                                 |             |                      |

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*including losses at Utility
Batch Electric Degree of Perfection

\[ \eta_P = \frac{\text{Exergy of useful products}}{\text{Exergy of inputs}} \]

Total Exergy In \((\text{Bin}) = 11,155,000 \text{ J}\)

Batch Electric Induction Melting of 1 kg of melt

Useful Exergy Out \((\text{Bout}) = 8,250,000 \text{ J}\)

Component | Exergy in (J) | Exergy in (J)
---|---|---
Metallics | 8,700,000 | 8,700,000
Electricity* | 2,455,000 | 2,455,000

\*not including utility losses

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Degree of Perfection

\[ \eta_P = \frac{8,250,000 \text{ J}}{10,420,000 \text{ J}} = 0.79 \]
Plasma Enhanced Chemical Vapor Deposition (CVD)
### Input Deposition Gases

<table>
<thead>
<tr>
<th>Species</th>
<th>Input mass (g)</th>
<th>Input moles or primary energy</th>
<th>Exergy (J)</th>
<th>%Total Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiH4</td>
<td>0.95</td>
<td>0.029579mol</td>
<td>40928.6</td>
<td>0.749</td>
</tr>
<tr>
<td>O2</td>
<td>0.49</td>
<td>0.015313mol</td>
<td>60.79</td>
<td></td>
</tr>
<tr>
<td>Ar</td>
<td>0.34</td>
<td>0.008511mol</td>
<td>99.5</td>
<td></td>
</tr>
<tr>
<td>N2</td>
<td>196.9</td>
<td>7.028779mol</td>
<td>4849.9</td>
<td></td>
</tr>
</tbody>
</table>

### Input Cleaning Gases

| CH4     | 69.41          | 4.326643mol                  | 3598253    |              |
| NF3     | 31.06          | 0.437453mol                  | 266931.6   |              |

### Input Energy

- Electricity: 2220000J  36.2

### Outputs

<table>
<thead>
<tr>
<th>Undoped Silicate Glass layer</th>
<th>Exergy (J)</th>
<th>%Total Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0248</td>
<td>0.000414mol</td>
<td>3.2667</td>
</tr>
</tbody>
</table>

---

Plasma enhanced CVD

---

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Chemical Vapor Deposition (CVD) of a 600nm Undoped Silicate Glass (USG) layer at 400°C

Total Exergy In (Bin) = 6,130,000J

Useful Exergy Out (Bout) = 3.3J

Component | Exergy in (J) |
---|---|
Input Gases | 45,900 |
Cleaning Gases | 3,865,000 |
Electricity* | 2,220,000 |

*not including utility losses

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Data from Sarah Boyd et. al. (2006)

Degree of Perfection:

$$\eta_p = \frac{3.267 \ J}{6,131,123 \ J} = 5.33 \times 10^{-7}$$
Reasons for a Low Efficiencies

• Inefficient use of materials
• Use of high exergy materials (ultra-pure)
• Use of high exergy Aux. mat’ls (CH₄)
• Low yields
• Low processing rates
Manufacturing’s Role in a Low Carbon Future

• Many small pieces
• Contribution to solutions
• Materials management
• Strong rate effect...
• Process redesign issues

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Most of these results can be found

- on our website: http://web.mit.edu/ebm/www/index.html