The Materials Which Make Up an Automobile

Understanding the Upstream Processes and Burdens Associated with Materials and Parts Production

TPP 123

Group Assignment

- The task for each group will be:
  - Propose a vehicle design which suits the goals of your interest group
    - Note: Design changes will be limited to changing the material from which the body-in-white is made
  - Propose a policy which will promote the development and adoption of your proposed vehicle

- Tools for detailed analysis
  - Cost models
  - Environmental inventory
  - Inventory evaluation tools
Why Do We Care About Material?

- Choice of material impacts the
  - Manufacturing process
  - Product performance
  - Cost
  - Environmental impact?

- Three materials are the prime candidates for use in automotive bodies
  - Actually three groups of materials
    - Steel
      - The current dominant material
    - Aluminum
    - Polymer composites
      - Ester Resin with Glass Fiber Reinforcement

Materials Matter -- Energy Use Primary / Secondary

- The choice of material and its source can have a big impact on the environmental impact of the product

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy for Primary Prod (MJ/kg)</th>
<th>Energy for Secondary Prod (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>189</td>
<td>27</td>
</tr>
<tr>
<td>Cu</td>
<td>100</td>
<td>45</td>
</tr>
<tr>
<td>Steel</td>
<td>40</td>
<td>18</td>
</tr>
<tr>
<td>Mg</td>
<td>285</td>
<td>27</td>
</tr>
<tr>
<td>Lead</td>
<td>41</td>
<td>8</td>
</tr>
<tr>
<td>Polyester</td>
<td>96</td>
<td>50</td>
</tr>
<tr>
<td>PP</td>
<td>74</td>
<td>42</td>
</tr>
</tbody>
</table>
What is in an automobile?

- Iron 13%
- Glass 3%
- Rubber 4%
- Other 3%
- Plastics 8%
- Aluminum 7%
- Other Nonferrous 3%
- Steel 59%
- Glass 3%
- Other 3%
- Plastics 8%
- Aluminum 7%
- Other Nonferrous 3%
- Steel 59%

Why Care About Automobile Recycling

- Autos are significant consumers of resources
  - Aluminum 19%
  - Lead 70%
  - Platinum 41%
  - Rubber >60%
  - Iron 35%
  - Steel 14%

[Bar chart showing consumption of various materials in automobiles and the total U.S. consumption.]
What is Steel?

Steel is iron with a small amount of carbon (~<1%).

Iron makes up 5% of earth's crust.

Steel first used ~1400 BC by Chalybes, SE of Black Sea.

Two major steps:

- Make Iron
  - Blast Furnace
- Make Steel
  - Basic Oxygen Furnace (BOF)

How Do We Make Steel?

- Steel is iron with a small amount of carbon (~<1%)
- Iron makes up 5% of earth's crust
  - Steel first used ~1400 BC by Chalybes, SE of Black Sea
- Two major steps:
  - Make Iron
    - Blast Furnace
  - Make Steel
    - Basic Oxygen Furnace (BOF)
Making Steel Step One - Blast Furnace

- **Raw Materials**
  - Iron Ore
    - *Usually iron oxides*
  - Coke
  - Limestone and/or other fluxes

- **What is happening?**
  - Carbon in coke serves as reducing agent
  - Fe₂O₃ + 3CO ↔ 2Fe + 3CO₂

![Diagram of Blast Furnace with inputs and outputs]

<table>
<thead>
<tr>
<th>Inputs (kg)</th>
<th>Outputs (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore</td>
<td>1600</td>
</tr>
<tr>
<td>Coke</td>
<td>450</td>
</tr>
<tr>
<td>Limestone</td>
<td>190</td>
</tr>
<tr>
<td>Blast Air</td>
<td>1300</td>
</tr>
<tr>
<td>Fuel</td>
<td>50</td>
</tr>
<tr>
<td>Top Gas</td>
<td>2300</td>
</tr>
<tr>
<td>Slag</td>
<td>300</td>
</tr>
<tr>
<td>Iron</td>
<td>1000</td>
</tr>
</tbody>
</table>

Making Steel Step Two - Basic Oxygen Furnace

- **Must reduce the amount of carbon in the iron**

- **Raw Materials**
  - Pig Iron
    - *From blast furnace*
  - Scrap
  - Limestone and other fluxes

- **Dissolved carbon is oxidized**

- **Releases about .25g particulates/ kg steel**

![Diagram of Basic Oxygen Furnace with inputs and outputs]

<table>
<thead>
<tr>
<th>Inputs (kg)</th>
<th>Outputs (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>865</td>
</tr>
<tr>
<td>Scrap</td>
<td>170</td>
</tr>
<tr>
<td>Limestone</td>
<td>80</td>
</tr>
<tr>
<td>Oxygen</td>
<td></td>
</tr>
<tr>
<td>Top Gas ~150 (CO₂)</td>
<td></td>
</tr>
<tr>
<td>Slag</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>1000</td>
</tr>
</tbody>
</table>
**Aluminum**

- **Aluminum makes up 8% of the earth’s crust**
  - Al production process discovered in 1886
- **Bauxite is the primary ore**
  - 40-60% Alumina
- **Two major steps:**
  - Extract Alumina from Bauxite
    - **Bayer Process**
  - Electrolytically reduce Aluminum from Alumina
    - **Hall-Heroult Process**

**Bayer**

Aluminum Step One - Bayer Process

- Because bauxite contains many minerals, the alumina must be extracted.
- Alumina is preferentially dissolved in NaOH
- Al(OH)₃ is precipitated out
- Al₂O₃ is calcined to Al₂O₃
- Remaining caustic sludge is referred to as red mud
  - Iron oxides give reddish color

### To Produce 1000kg of Al

<table>
<thead>
<tr>
<th>Product</th>
<th>Bauxite</th>
<th>NaOH</th>
<th>Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kg</td>
<td>4-5000</td>
<td>400</td>
<td>90</td>
</tr>
</tbody>
</table>

**Process Releases**

<table>
<thead>
<tr>
<th>Product</th>
<th>per Kg Al₂O₃</th>
<th>per Kg Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulates</td>
<td>100g</td>
<td>200g</td>
</tr>
<tr>
<td>Red Mud</td>
<td>1.75kg</td>
<td>3.5kg</td>
</tr>
</tbody>
</table>
Electrolysis in Step Two: Hall-Heroult Process

- Aluminum in alumina is electrolytically reduced
  - Anodes are made of carbon
  - Electrolyte, called cryolite, is mixture of \( \text{AlF}_3 \) & \( \text{Na}_3\text{AlF}_6 \)

To Produce 1000kg of Al

<table>
<thead>
<tr>
<th>Alumina</th>
<th>C Anodes</th>
<th>Cryolite</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900kg</td>
<td>450kg</td>
<td>20kg</td>
</tr>
</tbody>
</table>

Hall-Heroult Process

Aluminum 1000kg

Process Releases

<table>
<thead>
<tr>
<th></th>
<th>per Kg Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>1.6kg</td>
</tr>
<tr>
<td>Particulates</td>
<td>1.4g</td>
</tr>
<tr>
<td>SO2</td>
<td>8g</td>
</tr>
<tr>
<td>NOx</td>
<td>3g</td>
</tr>
<tr>
<td>HF</td>
<td>.25g</td>
</tr>
<tr>
<td>Fluorocarbons</td>
<td>some</td>
</tr>
<tr>
<td>Electricity</td>
<td>60MJ</td>
</tr>
</tbody>
</table>

How Do These Two Compare?

- Emissions per kg of product
  - Kilograms released for each kilogram produced

Emissions from Production

<table>
<thead>
<tr>
<th>Emissions from Production</th>
<th>Steel</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kg Released per Kg Produced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Massachusetts Institute of Technology
Cambridge, Massachusetts

MSL
Materials Systems Laboratory
What if We Look at an Entire Product?

- Emissions from two different BIW designs
  - Aluminum is still mostly worse

Emissions from Production

Why Look at Aluminum?

- Trade offs in other parts of vehicle life cycle
- Major reduction of BIW weight
  - Steel - 250 kg
  - Aluminum - 141 kg
  - Reduces vehicle fuel use and emissions
Polymer Usage in the Car

- Polymer usage has been growing in the car for 40 years

How are polymers used?

<table>
<thead>
<tr>
<th>Part</th>
<th>Main Plastics Types</th>
<th>Weight in Avg Car (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bumpers</td>
<td>PP, ABS, PC</td>
<td>10</td>
</tr>
<tr>
<td>Seats</td>
<td>PUR, PP, PVC,</td>
<td>13</td>
</tr>
<tr>
<td>Dashboard</td>
<td>PP, ABS, PA, PC, PE</td>
<td>15</td>
</tr>
<tr>
<td>Fuel systems</td>
<td>PE, POM, PA, PP</td>
<td>7</td>
</tr>
<tr>
<td>Body (including panels)</td>
<td>PP, PPE, UP</td>
<td>6</td>
</tr>
<tr>
<td>Under the hood components</td>
<td>PA, PP, PBT</td>
<td>9</td>
</tr>
<tr>
<td>Interior Trim</td>
<td>PP, ABS, PET, POM, PVC</td>
<td>20</td>
</tr>
<tr>
<td>Electrical components</td>
<td>PP, PE, PBT, PA, PVC</td>
<td>7</td>
</tr>
<tr>
<td>Exterior Trim</td>
<td>ABS, PC, PBT, ASA, PP</td>
<td>4</td>
</tr>
<tr>
<td>Lighting</td>
<td>PP, PC, ABS, PMMA, UP</td>
<td>5</td>
</tr>
<tr>
<td>Upholstery</td>
<td>PVC, PUR, PP, PE</td>
<td>8</td>
</tr>
<tr>
<td>Other reservoirs</td>
<td>PP, PE, PA</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>105</td>
</tr>
</tbody>
</table>
Polymer Processing

- Due to variety it is difficult to settle on one process
- Key steps:
  - Extraction
  - Distillation
  - Cracking
    - Yield of 85 - 95% -- product out / feedstock in
  - Polymerization
    - Yield of 99%
  - Forming

Automobile Production / Manufacturing

- Automobiles are Mass-Production Products
- What Does This Mean?
  - Annual Production Volumes On The Order Of 100,000
  - Production Rated On The Order Of 60-75 units/hour
  - Have To Be Affordable To A Large Market
- Contrast With Airplanes
  - Annual Production Volumes Less Than 1000
  - Production Rates On The Order Of 1/day
  - Specialized Markets
- These Differences Lead To Different Processing Requirements
What is Next?

- At this point, for both steel and aluminum, we are left with a large block of material called a billet.
- Before final processing, billets are flattened using rollers until they become sheets.
- Compared to the previous steps, the energy used and environmental releases are small.

Final Processing

- Current steel body parts are almost entirely made using one forming process - stamping.
- Metal sheets are pressed between two interlocking dies.
**Metal Stamping**

- Stamping is useful for both steel and aluminum
- Aluminum tends to require
  - Slower line rates
  - More aggressive lubrication
  - More rejects
- Why is stamping useful?
  - Fast cycle times
  - Approx. Seconds

**Polymer Forming**

In comparing material alternatives, we will look at polymer alternatives

- For cost modeling, we will look at one processing method - Sheet Molding using Sheet Molding Compound (SMC)
- SMC is made up of thermoset resin and glass fiber reinforcement
- SMC is pressed between two interlocking molds
Polymer Sheet Molding

- Advantages of SMC
  - Low equipment and tooling costs
  - Increased design flexibility

- Disadvantages
  - Long cycle times
    - Polymer must be reacted to make part solid
    - Reaction is initiated using heat
    - To ensure dimensional control - reaction occurs in mold
    - Molding equipment tied up during reaction
  - Requires different joining techniques