Introduction to Aluminum Sheet

The Aluminum Association
Presenter

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Presenter

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• Arconic
• Chief Engineer – Ground Transportation Products
Day 1 PM Agenda

1. Aluminum sheet production – flowpath
2. Aluminum alloys commonly used for BIW, closures
3. Sheet properties
4. Yield, ultimate and elongations as received
5. Properties after paint bake
6. Natural aging
7. Formability measures
8. Joining – Spot welding, SPR, Adhesives, flow drill screws, etc.
9. Design example – hood, door
10. Corrosion
11. Repair
General Wrought Product Flow Paths

1. Melting and alloying
2. Filtration and degassing
3. Ingot casting
4. Homogenization
5. Hot rolling
6. Cold rolling
7. Cold rolling
8. Possible batch anneal
9. Possible continuous heat treatment
10. Bonding pretreatment/lube
   • Customer operations
   1. Blanking/stamping
   2. Joining
   3. Painting (paint bake thermal cycle)
Typical Sheet Flow Path

Cast Ingot → Scalp → Homogenize → Hot Roll → Batch Anneal → Cold Roll

Inspect and Test → Slit, Blank and Oil → Solution Heat Treat → Quench

Pack and Ship →...
Automotive Aluminum Sheet: Production Flow Path and General Metallurgy

The Aluminum Association
Cast House Process Flow (DC Casting)

- Batch preparation
- Melting furnace
- Melting + Skimming
- Furnace treatment
- In line treatment
  - Degassing
  - Grain refiner
  - Filtration
- Casting furnace
- Casting
- Ingots
  - Source
Melting and Alloying

- Heavy gauge scrap is loaded into large melting furnaces
- Major alloying additions are made in the melting furnace
- The composition of the melted scrap is close to that of the desired alloy
- Molten metal from the melting furnace is transferred to the casting or holding furnace
- If necessary, final alloying additions are made in the holder. This is the last chance to control chemical composition
Degassing and Filtering

- **Degassing**: removal of hydrogen from molten metal by bubbling a mixture of gasses through the melt. Bubbles create a high gas-metal contact area (high ‘k”) and impurities are carried to the metal surface on the gas bubbles.

- **Fluxing**: causes impurities, such as alkaline, sodium, and lithium to rise to the surface of the bath. Skimming is done to remove the dross from the surface of the molten metal.

- **Filtration**: removal of inclusions from molten metal by passing through a filter media, typically different types of ceramic filters. Inclusions are retained at the surface of the filter media.
Ingot Casting

- Direct chill (DC) casting is the most common method of producing commercial aluminum ingots
- Developed in 1930’s – made possible higher quality, larger ingots, more alloys
- As the metal fills the mold and begins to solidify, the bottom block is lowered at a controlled rate. Water directly chills the solid Al shell
- 4 to 6 ingots can be cast at a time and can weigh 10-15 tons each
- Ingots are typically scalped before hot rolling

Scalping of Ingots

- **Scalping**: DC cast ingots are usually scalped before further processing to eliminate the rough as cast surfaces and possible other casting defects like coarse grain zones.
- Scalping also helps in getting to the desired thickness of the ingot for the hot rolling mill.

Source
Homogenization

- **Homogenization**: holding ingot at elevated temperature for some time to render the ingot microstructure suitable for hot rolling.

- Parts of the as-solidified microstructure can be altered by homogenization:
  - Redistribution of solute – elimination of micro-segregation
  - Dissolution of coarse soluble intermetallic particles
  - Modification of as-cast constituent phases
  - Control the nucleation and growth of dispersoids
  - Control the level of solute in solid solution
**Hot Rolling**

**Important considerations during hot rolling**

- **Recovery**
  - During rolling (dynamic recovery)
  - Between passes

- **Recrystallization**
  - Between passes (breakdown mill)
  - During coil cool (self anneal)

- **Alloying and microstructure**
  - Constituent particles less active as recrystallization nucleation sites
  - Interaction between precipitation and recovery and recrystallization

- **Strain rate**
  - Important in determining recovery and recrystallization kinetics
  - Thermal effects

- **Potential for variation across width, along length and through thickness of strip**
Cold Rolling

Important considerations during cold rolling

- Rolling below temperature for recrystallization (< 150°C).
- May need inter-annealing for some products to facilitate rolling to thin gauges.
- Key stage for control of mechanical properties
  - Strain hardened tempers
  - Response to annealing – O-temper and partially annealed products
- Also critical step for other features important to customer
  - Gauge, surface finish
- Most of heat of deformation contained within strip (and hence coil)
  - Strip temperature can rise to ~150°C
  - Controlled by amount of deformation – limited effect of speed due to strain rate insensitivity
- Cold rolling induces stored energy in the metal
Cold Rolling

Work Hardening due to Cold Rolling

- When material has been plastically deformed it requires greater stress to deform further.
- Work hardening happens during cold rolling, deep drawing, stretch forming
- Caused by creation and interactions of defects in the metal known as dislocations.
Annealing

- Thermal processing used to modify properties through control of recovery and recrystallization
- Important for control of mechanical properties and anisotropy (texture)
- Relevant to NHT and HT alloys

**Types of annealing treatment in sheet fabrication:**

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interannealing</td>
<td>Carried out at intermediate stage of a fabricating process so that material may be worked to a further degree.</td>
</tr>
<tr>
<td>Full annealing</td>
<td>Annealing to give a fully recrystallized, soft material (O-temper).</td>
</tr>
<tr>
<td>Partial annealing</td>
<td>Partial softening of a material which has been cold rolled to a temper harder than that required (some recrystallization may occur).</td>
</tr>
<tr>
<td>Recovery annealing</td>
<td>Annealing carried out such that no recrystallization occurs.</td>
</tr>
<tr>
<td>Self annealing</td>
<td>Annealing which occurs after hot rolling (re-roll gauge) without the application of a separate heat treatment.</td>
</tr>
</tbody>
</table>
Annealing

**Batch Annealing:**
- Processing of whole coils or blanks
- Relatively slow heating and long thermal exposure at PMT
- Typical treatment for full anneal (O-temper): 330°C, 2 hours
- Also used for inter-annealing

**Continuous Annealing:**
- Rapid heating and short thermal exposure promotes fine, equiaxed grain structure
- Solution Heat Treat or Anneal
- Coil pre-treatment
- Surface Inspection and Lubricant Application
- Examples:
  - Continuous Annealing Line (CAL)
  - Continuous Annealing and Solution Heat Treatment (CASH)
- CASH line:
  - Annealing of AA5xxx and AA6xxx
  - SHT of AA6xxx
Annealing

Annealing Curves:

- Annealing typically reduces strength of a cold rolled alloy and increases ductility.

Fabrication and Finishing of Aluminum Alloys (book), Joseph R. Davis

Novelis
Recovery and Recrystallization

Microstructural changes during heating after cold rolling

![Microstructural Images](As rolled, 280 °C, 300 °C, 320 °C)

![Graphs](Yield Stress vs. Annealing Temperature, Tensile Elongation vs. Annealing Temperature)
Recovery and Recrystallization

**Recovery:** Reduction in number of dislocations + rearrangement

**Recrystallization:** Formation of completely new grain structure

**Why is Recrystallization important?**
- Rolling process
  - Softens sheet for further processing
  - Lowers rolling loads and allows larger reductions
  - Reduces edge cracking during rolling
- Final product
  - Helps break down as-cast structure
  - Determines grain size at intermediate and final gauges
  - Reduces grain size – good for strength, formability and appearance
  - Controls crystallographic texture (anisotropy) of final product

Novelis
Recovery and Recrystallization

The amount of cold work affects the driving force for recrystallization, and the resultant final gauge grain size and aspect ratio.

**Hot Rolling**
- Conditions of temperature and strain rate such that recovery takes place during deformation
- Recrystallization can occur between rolling passes or following coiling

**Cold Rolling**
- Temperatures below that at which metal will recrystallize
- Recovery processes are not effective during deformation
- Strength rapidly increases due to work hardening
- Recovery can still take place following coiling

Novelis

- Increase of cold work → finer grain size after annealing
- 100µm
Effects of Texture - Roping

- In some aluminium alloy sheets, a rope-like profile parallel to the RD tends to develop when the sheet is stretched in the transverse direction (TD) and this phenomenon is termed roping.
- Alignment of crystallographic texture is one of the determinative factors for roping.
- Roping is in the form of ridges and valleys of different depths.
- Any processing that shortens the texture alignment, for example, inter-annealing, reduces the tendency to roping.
Precipitation Hardening

**Evolution of Precipitates During Processing:**

- Precipitation hardening is the primary strengthening mechanism for heat treatable alloys.
- Precipitates can form and/or dissolve at different stages of the processing of the sheets, but may not be required at all stages.
- Precipitation strengthening enables tailoring of properties - T4: soft and formable, T6: strong
Precipitation Hardening

**Solutionizing and Aging:**

- Precipitation hardening is achieved through solutionizing and aging heat treatment.

![Diagram showing solutionizing and aging process](image)

Novelis
Precipitation Hardening

**Solutionizing and Aging:**

- **W temper:** condition of a heat treatable alloy immediately after solution heat treatment and quenching – unstable state: spontaneously and rapidly age at room temperature towards the T4 temper.

- **Natural aging/T4 temper:** spontaneous and rapid aging of W temper alloy at room temperature.

The strength of 6xxx alloys increases with time at room temperature after solution heat treatment due to Natural aging.
Precipitation Hardening

- Precipitation hardening works by blocking movement of dislocations.
- Optimum precipitate size for blocking the dislocations - maximum strength.

Re-arrangement of atoms during aging

\[ \text{Aluminum atoms; } \ast \text{ Foreign atoms (e.g. Cu)} \]

Impact of Paint Bake Cycles

Typical Impact of Paint Bake Cycle

Stress (MPa)

Strain (%)
# Typical Mechanical Properties

## Exterior With Flat Hemming

<table>
<thead>
<tr>
<th>Grade</th>
<th>As received</th>
<th>After paint bake&lt;sup&gt;1&lt;/sup&gt;</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Typical Yield (MPa)</td>
<td>Typical Ultimate (MPa)</td>
<td>Typical T. Elong (%)</td>
</tr>
<tr>
<td>6EH</td>
<td>95-135</td>
<td>195-260</td>
<td>27</td>
</tr>
</tbody>
</table>
## Typical Mechanical Properties

### Exterior Without Flat Hemming

<table>
<thead>
<tr>
<th>Grade</th>
<th>As received</th>
<th>After paint bake</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Typical Yield (MPa)</td>
<td>Typical Ultimate (MPa)</td>
<td>Typical T. Elong (%)</td>
</tr>
<tr>
<td>6DR1</td>
<td>105-145</td>
<td>200-270</td>
<td>27</td>
</tr>
</tbody>
</table>
## Typical Mechanical Properties

### Interior Reinforcements

<table>
<thead>
<tr>
<th>Grade</th>
<th>As received</th>
<th>After paint bake</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Typical Yield (MPa)</td>
<td>Typical Ultimate (MPa)</td>
<td>Minimu m T. Elong (%)</td>
</tr>
<tr>
<td>6HS2</td>
<td>125-185</td>
<td>220-300</td>
<td>22</td>
</tr>
<tr>
<td>6HS2</td>
<td>125-185</td>
<td>220-300</td>
<td>22</td>
</tr>
</tbody>
</table>
# Typical Mechanical Properties

## 5754-O and 5182-O

<table>
<thead>
<tr>
<th>Grade</th>
<th>Typical Yield (MPa)</th>
<th>Typical Ultimate (MPa)</th>
<th>Minimum T. Elong (%)</th>
<th>Minimum U. Elong (%)</th>
<th>Minimum r&lt;sub&gt;ave&lt;/sub&gt;</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>5HF</td>
<td>105-155</td>
<td>250-300</td>
<td>27</td>
<td>20</td>
<td>0.60</td>
<td>5182-O</td>
</tr>
<tr>
<td>5ST</td>
<td>100-140</td>
<td>215-270</td>
<td>25</td>
<td>18</td>
<td>0.60</td>
<td>5754-O</td>
</tr>
</tbody>
</table>
Flat Hem Testing

15% pre-strain

11% pre-strain

7% pre-strain

Rating 2
Rating 1
Rating 1

Hem Rating Scale
1 – No cracking (mild to moderate orange peel is acceptable)
2 – Heavy orange peel
3 – Cracks visible with 3X magnification
4 – Cracks visible with naked eye
5 – Fracture or continuous crack along bend

Hem Rating Acceptance Scale
1 & 2: Fully Acceptable
3: Marginal – Subject to assembly plant decision
4 & 5: Not Acceptable

Figure 3: Flat hem specimens of 6022-T4E32 sheet tested after pre-straining to different levels.
The main alloys used for automotive body sheet are 5754 and 5182. Some 5052 also used in Europe.

- Used in the fully recrystallized condition – for maximum formability
- O-temper – no OEM requirements for surface quality after forming. Used in totally hidden locations, such as unexposed door inners
- RSS-temper – has OEM requirements for surface quality after forming. Used for exposed or partially exposed applications, such as some door, hood, deck lid inner applications, etc.
- Mg contents greater than 3.5 are not recommended for extended elevated temperature exposure > 150 deg F to avoid developing sensitivity to stress corrosion cracking
5182-O Stress Strain Curve
Mg in Aluminum - Luedering

- Deformation in metals occurs by the movement and multiplication of line defects called dislocations.
- In 5xxx alloys, Mg atoms interact very strongly with dislocations as they try to move through the aluminum crystal lattice. Consequently, two types of surface features can be created in 5xxx (and some other Mg containing alloys)...

Type A or ‘flamboyant’ Luedering  Type B or ‘serrated flow’ Luedering

Because of these features, 5xxx is not used for outer panels (Use 6xxx for outer panels)
Mg in Aluminum - Luedering

- Type A Luedering: associated with Yield Point Elongation (YPE)
- Type B Luedering: associated with serrated flow, (also known as PLC bands – Portevin Le Chatelier)
Questions?
Arc Length Calculation

K factor for calculating arc length during bending

Steel K = normally 0.38

Aluminum K = normally 0.43

For bend radius of T to Bend radius of 3T
Hood Example

Ref. A2MAC1
## Hood Example – Cadillac ATS

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Gauge (mm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hood outer</td>
<td>6000-IH-90</td>
<td>0.9</td>
<td>2.06</td>
</tr>
<tr>
<td>Hood inner</td>
<td>6000-IBR-100</td>
<td>0.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Palm reinforcement</td>
<td>6000-IBR-100</td>
<td>1.25</td>
<td>0.2</td>
</tr>
<tr>
<td>Hinge reinforcement</td>
<td>Al-S-6000-R-110-U</td>
<td>1.65</td>
<td>0.12 x 2 = 0.24</td>
</tr>
<tr>
<td>Latch reinforcement</td>
<td>Al-S-6000-R-110-U</td>
<td>1.25</td>
<td>0.18</td>
</tr>
<tr>
<td>Latch ring assembly</td>
<td>steel</td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td>3.8</td>
</tr>
</tbody>
</table>
Typical Hood Gauges

Hood Inner Supply Gauge (mm)

<table>
<thead>
<tr>
<th>Gauge Range (mm)</th>
<th>Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.80, 0.86]</td>
<td>25</td>
</tr>
<tr>
<td>(0.86, 0.93)</td>
<td>15</td>
</tr>
<tr>
<td>(0.93, 0.99)</td>
<td>10</td>
</tr>
<tr>
<td>(0.99, 1.06)</td>
<td>5</td>
</tr>
</tbody>
</table>

Hood Outer Supply Gauge (mm)

<table>
<thead>
<tr>
<th>Gauge Range (mm)</th>
<th>Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.84, 0.88]</td>
<td>5</td>
</tr>
<tr>
<td>(0.88, 0.93)</td>
<td>25</td>
</tr>
<tr>
<td>(0.93, 0.98)</td>
<td>10</td>
</tr>
<tr>
<td>(0.98, 1.03)</td>
<td>5</td>
</tr>
</tbody>
</table>
Affordable Aluminum Door Concept

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## Affordable Aluminum Door Concept

### CAE Overview (1): Static Loadcases

<table>
<thead>
<tr>
<th>Loadcase</th>
<th>Requirement</th>
<th>Steel Benchmark</th>
<th>Aluminum Door 5x-6x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door sagging</td>
<td>Max strain: 10 mm</td>
<td>2.24 @ 10°, 2.35 @ 70°</td>
<td>1.12 @ 10°, 1.12 @ 70°</td>
</tr>
<tr>
<td></td>
<td>Residual strain: &lt;1 mm</td>
<td>0.5 mm</td>
<td>0 mm</td>
</tr>
<tr>
<td>Wind overload</td>
<td>Max. opening: 6°</td>
<td>1.3°</td>
<td>1.37°</td>
</tr>
<tr>
<td></td>
<td>Residual opening: &lt;1°</td>
<td>0.33°</td>
<td>0.03°</td>
</tr>
<tr>
<td>Waistline stiffness</td>
<td>Max strain: 3 mm</td>
<td>0.07 mm</td>
<td>0.23 mm</td>
</tr>
<tr>
<td></td>
<td>Residual strain: none</td>
<td>0.01 mm</td>
<td>0 mm</td>
</tr>
<tr>
<td>Window Frame stiffness</td>
<td>Max strain: 3 mm</td>
<td>0.03 mm</td>
<td>0.6 mm</td>
</tr>
<tr>
<td></td>
<td>Residual strain: none</td>
<td>0.09 mm</td>
<td>0 mm</td>
</tr>
</tbody>
</table>
# Affordable Aluminum Door Concept

## CAE Overview (2): Dynamic Load Cases

<table>
<thead>
<tr>
<th>Loadcase</th>
<th>Requirement</th>
<th>Steel Benchmark</th>
<th>Aluminum Door 5x-6x</th>
</tr>
</thead>
</table>
| FMVSS 214S Pole Impact | Av on 152 mm > 10 kN  
Av on 304 mm > 16 kN  
Peak on 457 mm > 37 kN | 19.8 kN  
37.5 kN  
85.9 kN | 17 kN  
39 kN  
74 kN | ✓ |
| Door Crush        | Peak load > 60kN            |                 |                     |

Note: Aluminum concepts have been simulated with:
- 5x6x: SIB 6x 2.5 mm instead of 2 mm
- 6x uni: SIB 7075 2 mm instead of 1.5 mm

Steel: >100 kN  
5x6x: 78.5 kN (60 kN @ 32mm)  
6x uni: 76.5 kN (60 kN @ 28mm)
Affordable Aluminum Door Concept

<table>
<thead>
<tr>
<th>AFFORDABLE DOOR CONCEPTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5x-6x</strong></td>
</tr>
<tr>
<td><strong>Materials:</strong></td>
</tr>
<tr>
<td>Inner panel:</td>
</tr>
<tr>
<td>AA 5082, 1.2 mm Fusion™ 6HF - s200 RW Advanz™ 6HF - e200 Advanz™ 6HS*</td>
</tr>
<tr>
<td>Window Frame Reinf.:</td>
</tr>
<tr>
<td>SIB:</td>
</tr>
<tr>
<td>Window Frame Section:</td>
</tr>
<tr>
<td>Optimized for deep drawing &amp; joining (Arplas)</td>
</tr>
<tr>
<td>Joining Methods:</td>
</tr>
<tr>
<td>1. Spot welding (Arplas)</td>
</tr>
<tr>
<td>2. SPR</td>
</tr>
<tr>
<td>3. Adhesive</td>
</tr>
<tr>
<td>Part count/ Weight:</td>
</tr>
<tr>
<td>16 / 10.0 kg</td>
</tr>
</tbody>
</table>

Comparison process costs for door in white from different materials:
- Steel Benchmark: 17.7 kg, €15.33
- Affordable Aluminum Door: 5x-6x, 10.0 kg, €17.91
- Affordable Aluminum Door: 6x uni, 9.5 kg, €17.13

<4 €/kgs

2019 Aluminum Design Workshop
Sustainability

**Aluminum Is More Sustainable Today Than Any Other Period In History**

More than 75% of all primary aluminum for automotive applications in North America is smelted in Quebec using hydropower, resulting in the lowest production carbon footprint for the industry.

Most aluminum automotive parts also contain recycled aluminum, of which the energy demand and carbon footprint is just a tiny fraction of primary aluminum. Combining these two factors, the production phase emissions of aluminum parts does not increase when heavier counterparts are replaced. The significant reductions during vehicle’s driving and end-of-life phases makes aluminum stand out as the best material to reduce life cycle emissions.
Life Cycle Assessment

Reducing vehicle weight with aluminum increases fuel economy while cutting both tailpipe and life cycle emissions.

Lighter vehicles simply need less energy (fuel or battery power) to move.

In 2015, the Automotive Science Group found the Ford F-150 holds the smallest life-cycle carbon footprint of any full-size truck in North America.

The key...automotive aluminum. Reduced vehicle weight means elevated performance and reduced environmental burdens associated with raw material mining and processing. (Source: The Automotive Science Group)

Several third-party North American LCA studies prove aluminum’s outstanding ability to reduce life cycle energy demand and GHG emissions of vehicles. Including recent studies conducted by the Natural Resources Canada (Dubreuil et al 2012), Oak Ridge National Laboratory (Das 2014), Ford Motor Company & Magna International (Bushi et al 2015) and Athena Institute (Bushi 2018).

A literature review conducted by a team of U.S. EPA researchers on 26 life cycle assessment (LCA) studies concludes “most of the LCAs demonstrated that aluminum-intensive designs were able to achieve the largest reductions in life-cycle energy use and GHG impacts” (Hottle et al 2017).
Recycling

Jaguar Land Rover and Ford Motor Company pioneered closed-loop recycling of aluminum scrap in their manufacturing efforts. Aluminum can be recycled repeatedly. As a result, these industry-leading automakers tap into an endlessly renewable supply of aluminum through their operations.

Ford’s F-150 manufacturing plants recycle enough aluminum to produce 30,000 new trucks per month. (Source: Ford Motor Company)

At the end of a vehicle’s life, automotive aluminum is fully and appropriately recycled and reused for automotive parts.

Two studies conducted by scientists at the Worcester Polytechnic Institute showed that metal recovery of automotive aluminum at the end-of-life recycling is as high as 96% (Source: WPI 2016, 2018)
Questions?
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