Introduction to Aluminum Sheet

The Aluminum Association
Presenter

Russ Long
- Arconic
- Chief Engineer – Ground Transportation Products
Rashmi Mohanty, Ph.D.

- Novelis
- Principal Scientist, R&D Automotive
Day 1 PM Agenda

1. Aluminum Sheet Production – flowpath
2. Aluminum alloys commonly used for BIW and 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 – aluminum hood, aluminum door
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

1. Cast Ingot
2. Scalp
3. Homogenize
4. Hot Roll
5. Batch Anneal
6. Cold Roll
7. Inspect and Test
8. Slit, Blank and Oil
9. Pack and Ship
10. Solution Heat Treat
11. Quench
Cast House Process Flow (DC Casting)

- **Batch preparation**
- **Melting + Skimming**
- **Melting furnace**
- **Casting**
- **Casting furnace**
- **Furnace treatment**
- **In line treatment**
  - **Degassing System**
  - **Degassing**
  - **Grain refiner**
  - **Filtration**

**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

R. Nadella et al, Progress in Materials Science, 53 (3), 2008
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.
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
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
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.

Elements of Metallurgy and Engineering Alloys
F.C. Campbell, editor, p 487-508
DOI: 10.1361/emea2008p487
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 Curves:

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

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

Microstructural changes during heating after cold rolling

Novelis

As rolled

280 °C

300 °C

320 °C

Novelis

Recovery

Recrystallization

YIELD STRESS (MPa)

ANNEALING TEMPERATURE (°C)

TENSILE ELONGATION (%)
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
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
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.
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

- **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

Artificial aging curves for AA6061 alloy

Impact of Paint Bake Cycles

Typical Impact of Paint Bake Cycle

- 2% PS + 20 min at 185 deg C
- as received
- 0% PS + 20 min at 185 deg C
- T6
**Typical Mechanical Properties – Exterior with Flat Hemming**

<table>
<thead>
<tr>
<th>Grade</th>
<th>As received</th>
<th>After paint bake(^1)</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>Minimum 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 $r_{ave}$</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

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’ Luderling  Type B or ‘serrated flow’ Luderling

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><strong>Totals</strong></td>
<td></td>
<td></td>
<td><strong>3.8</strong></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>10</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>5</td>
</tr>
<tr>
<td>(0.98, 1.03)</td>
<td>5</td>
</tr>
</tbody>
</table>
Affordable Aluminum Door Concept

Novelis

© 2017 Novelis

© 2018 Aluminum Association Design Seminar
# 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 10° and 70° opening, Load: 750 N</td>
<td>Max strain: 10 mm, Residual strain: &lt;1mm</td>
<td>2.24 @ 10°, 2.35 @ 70° 0.5 mm</td>
<td>✓ 1.12 @ 10°, 1.12 @ 70° 0 mm</td>
</tr>
<tr>
<td>Wind overload, Load: 400 N</td>
<td>Max. opening: 6°, Residual opening: &lt;1°</td>
<td>1.3° 0.33°</td>
<td>✓ 1.37° 0.03°</td>
</tr>
<tr>
<td>Waistline stiffness, Load: 100 N</td>
<td>Max strain: 3 mm, Residual strain: none</td>
<td>0.07 mm 0.01 mm</td>
<td>✓ 0.23 mm 0 mm</td>
</tr>
<tr>
<td>Window Frame stiffness, Load: 100 N</td>
<td>Max strain: 3 mm, Residual strain: none</td>
<td>0.03 mm 0.09 mm</td>
<td>✓ 0.6 mm 0 mm</td>
</tr>
</tbody>
</table>
Affordable Aluminum Door Concept

### CAE OVERVIEW (2): DYNAMIC 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>FMVSS 214S Pole Impact</td>
<td>Av on 152 mm &gt; 10 kN Av on 304 mm &gt; 16 kN Peak on 457 mm &gt; 37 kN</td>
<td>19.8 kN</td>
<td>17 kN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>37.5 kN</td>
<td>39 kN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85.9 kN</td>
<td>74 kN</td>
</tr>
<tr>
<td>Door Crush</td>
<td>Peak load &gt; 60kN</td>
<td>Steel: &gt;80 kN</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel: &gt;100 (60 kN @ 36mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Note: Aluminum concepts have been simulated with 5x6x: S1B 6x 2.5 mm instead of 2 mm 6x uni: S1B 7075 2 mm instead of 1.5 mm</td>
<td>5x6x: 76.5 kN (60 kN @ 32mm)</td>
<td>6x uni: 76.5 kN (60 kN @ 28mm)</td>
</tr>
</tbody>
</table>
## Affordable Aluminum Door Concept

### Affordable Door Concepts Table

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Inner panel: AA 5082, 1.2 mm</th>
<th>Window Frame Reinf.: Fusion™ 6HF - s200 RW</th>
<th>Outer Panel: Advanz™ 6HF - e200 Advanz™ 6HS*</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Window Frame Section:</th>
<th>Optimized for deep drawing &amp; joining (Arplas)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Joining Methods:</th>
<th>1. Spot welding (Arplas)</th>
<th>2. SPR</th>
<th>3. Adhesive</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Part count/ Weight:</th>
<th>16 / 10.0 kg</th>
</tr>
</thead>
</table>

---

### Graph: Comparison process costs for door in white from different materials

- **Steel** Benchmark: 17.7 kg, €15.33
- **Novelis Aluminum Door**: 6x-6x, 10.0 kg, €17.91
- **Novelis Aluminum Door-Ex uni**: 9.5 kg, €17.13

<4 €/kgs
Questions?
Tell Us How We Did!

1. Open a browser on your laptop, tablet or mobile device

2. Visit: pollev.com/aassociation001

3. Give us feedback!