Alcoa Aluminum: Rolled Products

Dr. J. Daniel Bryant
Technical Fellow, Alcoa Technical Center (Pittsburgh, Pennsylvania)

March 18, 2015
Alcoa covers every stage of aluminum production and is a leader in major end markets.

**Operations**

**Upstream (41%)**
- Bauxite mining
- Alumina refining
- Aluminum smelting
- Aluminum recycling

$7.5bn

**Midstream (33%)**
- Aluminum Sheet & Plate
- Aluminum Can Stock

$6.1bn

**Downstream (26%)**
- Fastening Systems
- Super-alloy castings
- Wheel & Transportation
- Building & Construction
- Forgings & Extrusions  $4.8bn

**Primary Aluminum**

**Automotive Transportation**

**Packaging**

**Building/Construction**

**Aerospace**

**Industrial**

**Oil & Gas**

**Consumer Electronics**
Global Rolled Products – a global business spread across 5 continents

**GRP business unit structure and operating locations**

Market-facing Global Business Units… …with a Global footprint

### Alcoa Global Packaging (AGP)

**Product Lines:**
- Can (Beverage & Food)
- Specialty Foil
- Industrial

### Aero, Transportation & Industrial (ATI)

**Product Lines:**
- Commercial Aerospace
- Auto Body & Brazing
- Industrial
- Commercial Transportation

### China & Consumer Electronics (CRP)

**Product Lines:**
- Can (Beverage)
- Brazing
- Commercial Transportation
- Consumer Electronics
Research Directions at Alcoa Technical Center in Sheet and Plate Products:

1. Improve Process Efficiency:
   - improve conversion (secondary processing) efficiency
   - reduce scrap (improve recovery – planned and unplanned)
   - improve output (ROC)
   - reduce labor content per kg

2. Improve Sustainability
   - reduce effluent (solids, volatiles, etc.)
   - reduction in greenhouse gas generation
   - improve recycling

3. Introduce Improved Products
   - superior process performance (for our processes)
   - superior process performance (for our customers’ processes)
   - superior service performance (for their customers)
The fundamentals: What is rolling?

….a process in which a material is passed between two parallel rotating rolls, causing the material to be reduced in thickness and increased in length.

If there is no lateral spreading of the sheet, i.e. $\varepsilon_w = 0$, (usually when $w >> t$) then $\varepsilon_t = -\varepsilon_l$ and we call this plane strain.

If there is any spread in the width direction ($\varepsilon_w \neq 0$) it is no longer plane strain.
Example: Davenport Works - 65 Years Serving Our Customers

- Began production in 1948
- $716M in Total Assets
- 132 acres under roof
- 2,300 employees
- 110 alloys, 8,000 specs
- 1,100 global customer locations

Operations:
- Metal Purification
- Casting
- Rolling, Stretching
- Sawing/Machining
- Heat Treatable & Non-Heat Treatable
- Sheet & Plate

Diversified Product Base:
- Aerospace and Defense Sheet & Plate
- Automotive Sheet
- Industrial Sheet & Plate
- Commercial Transportation
Sheet and Plate Manufacturing at Davenport Works

- Ships 500 million lbs/yr. or 1.3 M lbs. a day of finished product
- Produces plate products up to 220” wide and 110 feet long
- Three reversing hot mills, 220” wide, 160” wide, 144” wide
- 100” 5 stand hot mill
- Two 100” cold mills
- 86” wide continuous heat treat line
- *New 88” wider continuous heat treat line (exclusively for automotive)*
- Two vertical heat treat lines
Theme:
Understanding the metallurgical thinking and microstructural changes as we follow aluminum through the processing flowpath....
Multiple ingots are cast at a single composition using direct chill (DC) casting.

To remove “liquated” layer and provide a flat surface for rolling, ingots are scalped prior to homogenization.
Solidifies as dendritic grains (also known as: cells/crystals)

Non-uniform tinting within grains is due to the non-uniform distribution of elements such as Mg, Mn, etc.

Constituent Particles

250 microns
Tracking the Metallurgical Evolution: As-Cast Microstructure

**Constituent Particles**

Si - much of it combines with Mg to form Mg$_2$Si particles. (these appear dark as-polished)

Fe - very low solubility in solid Al. It tends to form Al$_3$Fe and Al$_{12}$Fe$_3$Si$_2$ type particles in the last stages of solidification – these are constituents.

Aluminum Matrix - has Mg, Mn*, Cu, etc. dissolved within it - usually not uniformly distributed.

* Mn, like Fe, is also has low solubility in solid Al - but is unable to partition into liquid during solidification and gets trapped in solid. Will come out during ingot homogenization as dispersoids.

5182 Can End Stock
Mn, although highly insoluble in Al was trapped in solid during solidification.

During the long thermal exposure during ingot homogenization, Mn is able to diffuse and form discrete dispersoids of Al$_6$(Mn,Fe)

...and perhaps also some Al$_{12}$(Mn,Fe)$_3$Si$_2$
Sheet and Plate Manufacturing: Hot Rolling

What is the advantage of a smaller work roll diameter?

Load = Pressure x Area
Load = Pressure x (W x L)
So, Load \( \propto L \)

... and a smaller work roll diameter therefore results in lower loads.
220-in. Hot Reversing Mill - Davenport
Ingots are rolled down to progressively thinner gauges in reversing mills. Deforming becomes more *plane strain* (the sheet maintains its width and gets progressively longer) as rolling proceeds. Rolled plate seen on the run-out table to the right...
5-Stand Hot Continuous Mill
used for rolling to sheet thicknesses ("hot band")
Hot rolled coils, with gauges in the 2mm to 8 mm range, are now either given an anneal treatment or are passed directly to cold rolling to reduce the gauge and modify the crystallographic texture.
Hot rolled products can be come off the mill fully recrystallized, partially recrystallized or unrecrystallized, depending on the alloy, the reduction schedules and the rolling temperature.

When recrystallization occurs the elongated, strained hot rolled grains are replaced by a new set of low aspect ratio, strain-free grains.

Hot rolled product, therefore, can be either *self-annealed* or *unannealed*.

A *batch anneal* (also called an hot line anneal or intermediate anneal) can be imposed to complete recrystallization, if so desired...
# Tracking the Metallurgical Evolution: *Cold Rolling and Annealing*

**As-Hot Rolled 5xxx...**

<table>
<thead>
<tr>
<th>Path 1</th>
<th>Path 2</th>
<th>Path 3</th>
<th>Path 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Roll 50%</td>
<td>Cold Roll 33%</td>
<td>Anneal</td>
<td>Cold Roll 60%</td>
</tr>
<tr>
<td>Anneal</td>
<td>Anneal</td>
<td></td>
<td>60%+</td>
</tr>
<tr>
<td>Cold Roll 20%</td>
<td>Cold Roll 40%</td>
<td>Cold Roll 60%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Yield Strength</th>
<th>Yield Strength</th>
<th>Yield Strength</th>
<th>Yield Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>88 MPa</td>
<td>91 MPa</td>
<td>101 MPa</td>
<td>105 MPa</td>
</tr>
</tbody>
</table>

![Images](image1.png) ![Images](image2.png) ![Images](image3.png) ![Images](image4.png)
After exiting the hot continuous mill, the strip *recrystallizes*....

Some/many of the recrystallized grains are of the **cube** orientation....

When the cube faces of face centered cubic crystal structure of Al is lays in the sheet plane & FCC edges are parallel to rolling direction, we have **cube texture**.
The cube texture from hot rolling imparts ‘0-90°’ earing tendencies to the recrystallized strip….
The cold rolling texture causes ears to be formed at all locations \( \sim 45^\circ \) from RD (actually closer to \( 48^\circ \))....

![Graph showing 45° earring of rolling texture](image)

![Diagram showing crystallographic texture and earring](image)
So, the secret to low earing is to product the right amount of cube texture in the hot rolling process to balance with the texture subsequently introduced in cold rolling to final gauge….

So while zero earing is only possible with random textures, earing can be reduced by balancing crystallographic textures introduced in different steps in the rolling process…
Crystallographic Texture and Earing

Real World Example: Aluminum Can Stock
AA3104

Real World Example: Aluminum End Stock
AA5182
Crystallographic Texture Control is Important for Manufacturability:

- Forming
- Hemming
- Isotropy in Properties

But it is also Important for Service Performance:

- Surface Appearance
Surface appearance in aluminum autobody sheet can be compromised by bands of cube oriented grains that are remnants from the hot rolling process. These “ridging” or “roping” lines are a cause for rejection....
Examples of Alcoa Products Used on Commercial Vehicles

1 in 3 trucks in North America ride on Alcoa Wheels

Typical Steel truck wheel weighs 35 kg versus typical aluminum truck wheel weighs 21 kg (roughly 40% savings)
• 95% of gasoline tankers are aluminum in the US

• Powered Bulk haul trailers with pressurized material movement are normally aluminum in the US

• Dump truck boxes in aluminum are common
### Application of Aluminum in Commercial Transportation

<table>
<thead>
<tr>
<th>Use</th>
<th>Alloy</th>
<th>Key Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis, Trailer Frames</td>
<td>6061-T6 extrusion</td>
<td>Strength, fatigue*</td>
</tr>
<tr>
<td>Side Sheets</td>
<td>3004, 5052-H291</td>
<td>Painted, durability</td>
</tr>
<tr>
<td>Roof</td>
<td>3003-H1x</td>
<td>Wide width</td>
</tr>
<tr>
<td>Fuel Tanks</td>
<td>5052-O</td>
<td>Impact resistance*</td>
</tr>
<tr>
<td>Compressed Air</td>
<td>5083, 5754, 5154</td>
<td>Impact resistance*</td>
</tr>
<tr>
<td>Wheels</td>
<td>6061-T6</td>
<td>Fatigue, surface, wear</td>
</tr>
<tr>
<td>Cab Sheets</td>
<td>6022, 6111-T4, 5182-O</td>
<td>Formability</td>
</tr>
<tr>
<td>Bumpers</td>
<td>6061, 5xxx</td>
<td>Surface, strength</td>
</tr>
<tr>
<td>Trim</td>
<td>Various 3xxx, 5xxx</td>
<td>Good surface</td>
</tr>
</tbody>
</table>
Alcoa “invented“ aluminum alloy development...

- First recorded alloy 1100 (2S) developed in 1888
- 3003 (3S) followed in 1906
- First important heat treated alloy was 2017 (1916), followed by 2025 (1921), and 2014 (1928)
- 2024 appeared in 1932 and is still a workhorse alloy for aerospace
- First important high strength alloy was 7075 (1942)
- Large majority of commercially important aerospace alloys developed by Alcoa

...and we have been innovating ever since
Important aerospace alloys developed by Alcoa:
- 2014, 2017, 2024, 2124, 2219, 2519, 2524, 2026, 2624, 2090, 2099, 2060, 2055
- 6061, 6013
- 7075, 7175, 7475, 7178, 7050, 7150, 7055, 7085, 7255

Important tempers developed by Alcoa
- T73, T76, T74, T77
The product of aging of Al-Cu-Li Alloys: strengthening precipitates...

Figure 1: Aluminum Plate Product Typical Properties vs. Year First Used on Specific Aircraft
3rd Generation Al-Li Alloys have been developed by optimizing alloy composition, TMP and tempering for a good balance of:

- Density
- Strength and toughness balance
- Low anisotropy of mechanical properties
- Fatigue crack growth resistance
- Corrosion resistance
- Thermal stability
- Manufacturability

Attractive applications are being identified for lower wing, upper wing, fuselage, thick sections of civil transport in addition to military and space applications.
1. **Manufacture of Rolled Aluminum Products is a Multi-Step Operation**
   - Ingot Casting
   - Homogenization
   - Scalping
   - Hot Rolling
   - Intermediate Annealing
   - Cold Rolling
   - Heat Treatment (coil annealing, continuous heat treatment, aging)

2. **Thermo-Mechanical Processing is used to Control Product Gauge, Properties and Anisotropy**
   - Strength
   - Toughness
   - Corrosion Resistance
   - Surface Appearance
   - Crystallographic Texture

3. **The Microstructural Evolution through the Process Guides Metallurgical Decisions**