Aluminium alloys

Mechanical Metallurgy school  
Oct. 23-29 2016 - Porquerolles

J. Chevy, C-TEC - Contellium Technology Center - Voreppe - France
Outline

I. History of aluminium

II. Overview of Aluminium properties vs. other materials

III. Aluminium transformation schedule

IV. Lightweighting as a driver for material development

   IV-1 Overview

   IV-2 Examples of the link between customer need - properties - microstructure and process

      IV-2a Automotive

      IV-2b Aerospace

      IV-2c Packaging
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Aluminium can be obtained from aluminium oxide (alumina) or aluminium Chloride

- **1825** - Hans-Christian Orsted (Danish chemist) first to extract aluminium using a chemical reaction (low purity metal)

**Aluminium oxide**
- synthetic
- Natural (corundum) can form ruby and sapphire

**Aluminium chloride**
Aluminium was once expensive and hard to produce

- **1854** - Henri Sainte-Claire Deville (French scientist) develops first commercial means of extracting aluminium (still very expensive)
- **1855** – 12 ingots of aluminium displayed at the *Exposition Universelle* held by Napoleon III
- **1852-1870** - Napoleon III (President of Second French Republic and later Emperor of Second French Empire) reportedly held a banquet where the most honoured guests were given aluminium utensils. Those less honoured were given gold utensils.
- **1884** – Aluminium chosen as capstone of the Washington Monument
The Hall-Heroult and Bayer processes made Aluminium producible on an industrial scale

- **1886** – Charles Hall (American student at Oberlin College) and Paul Heroult (French engineer) separately develop electrolysis method to extract aluminium from aluminium oxide

- **1887** – Karl Josef Bayer (Austrian engineer) develops process to extract aluminium oxide from bauxite

- **1888** – The Pittsburgh Reduction Company (present-day Alcoa) is created in the USA to produce pure aluminium industrially

- **1889** – Aluminium Industrie (present-day Rio Tinto Alcan) begins producing aluminium in Switzerland
Historical markers for aluminium products

- Existence of Aluminum theorized (1808)
- First Extraction of Aluminum (1825)
- First commercial extraction process (1854)
- Bayer Process Invented (1887)
- Hall-Heroult Process Invented (1886)
- aluminium body in a sports car (1899)
- Wright brothers use aluminium in the engine of their biplane (1903)
- 2-piece aluminium can (1959)

Timeline:

1800
1850
1900
1950
2000
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## Basic property comparisons
(approximate values or ranges)

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>Titanium</th>
<th>Steel</th>
<th>Mg</th>
<th>Aero composite (epoxy-C-fibre)</th>
<th>Auto composite (epoxy-glass fibre)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
<td>2.7</td>
<td>4.5</td>
<td>7.9</td>
<td>1.7</td>
<td>1.7</td>
<td>1.8</td>
<td>g/cm³</td>
</tr>
<tr>
<td><strong>Elastic modulus</strong></td>
<td>70</td>
<td>115</td>
<td>210</td>
<td>45</td>
<td>100 – 400</td>
<td>50 – 100</td>
<td>GPa</td>
</tr>
<tr>
<td><strong>Approximate maximum use T°C</strong></td>
<td>250</td>
<td>600</td>
<td>600</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>°C</td>
</tr>
<tr>
<td><strong>Electrical resistivity</strong></td>
<td>28</td>
<td>420</td>
<td>96</td>
<td>44</td>
<td>10000</td>
<td>Huge</td>
<td>nΩ·m</td>
</tr>
<tr>
<td><strong>Corrosion resistance</strong></td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor, except stainless</td>
<td>Poor</td>
<td>Immune, but sensitive to humidity</td>
<td>Immune, but sensitive to humidity</td>
<td></td>
</tr>
</tbody>
</table>

- **Lower density than most high volume metals**
- **Lower modulus than most high volume metals and C-fibre composites**

**Notes:**
- Lower density than most high volume metals
- Lower modulus than most high volume metals and C-fibre composites
- Low electrical resistivity
- Good corrosion resistance vs. most metals
Higher strength alloy families exist but in general:

- **5182-O**
- **6016-T4**
- **6016-T64**
- **6082-T6**
- **6065-T6**
- **5182-H19**
- **2024-T3**
- **7020-T6**
- **7046-T6**
- **7075-T6**
- **7449-T79**

**Al-Mg**

**Al-Mg-Si-Cu**

**Al-Cu-Mg-(Li)**

**Al-Zn-Mg**

**Al-Zn-Mg-Cu**

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**A80 [%]**

**Rp0.2 [MPa]**
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Aluminium production goes through series of mechanical and heat treatments that all contribute to final properties.
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Casting produces a workable piece of material.
Casting produces a workable piece of material

- Yields composition needed for a given alloy (alloy series determined by elements added)
- Provides a workable piece of material (e.g. for hot rolling or extrusion)
- Ingot $200 < \text{thickness} < 500 \text{ mm}$, $600 < \text{width} < 2500$  
  
Billet $100 < \text{diameter} < 500\text{mm}$

### Billets for extrusion

<table>
<thead>
<tr>
<th>Aluminum Alloy Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>2xxx : Cu, (Mg)</td>
</tr>
<tr>
<td>2xxx (Li) : Cu, Li (Mg, Ag, Zn)</td>
</tr>
<tr>
<td>3xxx : Mn</td>
</tr>
<tr>
<td>4xxx : Si</td>
</tr>
<tr>
<td>5xxx : Mg</td>
</tr>
<tr>
<td>6xxx : Si, Mg, Cu</td>
</tr>
<tr>
<td>7xxx : Zn, Mg, Cu</td>
</tr>
<tr>
<td>8xxx : Special Alloys (exotic compositions)</td>
</tr>
</tbody>
</table>

### Grain Size Control

- Cr
- Zr
- Mn
- Sc

### Impurities (Fe and Si*)

* Except for 4XXX and 6XXX
Recycling during casting reduces the material price and impact on environment

- The use of recycled material reduces price
- Recycled material introduces impurities that can reduce performance
- **End of life recycling rate:** amount of material recycled throughout the entire life cycle (~90% for automotive and transportation, ~70% for beverage cans)

<table>
<thead>
<tr>
<th>Machining Chips</th>
<th>Manufacturing Scrap</th>
<th>Bowls/sows (left over metal from casting)</th>
<th>Ingot Scrap</th>
<th>Heads and butts of ingots</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Machining Chips image]</td>
<td>![Manufacturing Scrap image]</td>
<td>![Bowls/sows image]</td>
<td>![Ingot Scrap image]</td>
<td>![Heads and butts of ingots image]</td>
</tr>
</tbody>
</table>
Casting produces a workable piece of material

<table>
<thead>
<tr>
<th>Major elements (hardening)</th>
<th>Minor elements (grain structure)</th>
<th>Impurities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>Cu</td>
<td>Mg</td>
</tr>
<tr>
<td>Min</td>
<td>3.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Max</td>
<td>4.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Semi-continuous casting (Vertical Direct-Chill casting)
  - Pour liquid metal on top, pull solid metal at bottom
  - Temperature of liquid metal >700°C
After casting, composition is heterogeneous at different scales

- At the microscale: Layers more and more enriched with eutectic elements are solidified from the solidification nucleus, then the residual eutectic liquid is solidified in the form of a eutectic aggregate.

![Diagram showing Al-7%Si phase diagram and microstructure of Al-Si alloy](image)
After casting, composition is heterogeneous at different scales

- At the macroscale: because of relative movement of solid and liquid phases during solidification
  - Convection due to temperature and composition gradients

- Casting temperature, speed, grain refinement and slab thickness have a major influence on macrosegregation
Aluminium production goes through series of mechanical and heat treatments that all contribute to final properties.

Heat treatments after casting give a uniform material that can be deformed.
### Heat treatments after casting, but before rolling

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stress-relieving</strong></td>
<td>Treatment which is performed after casting aiming to heat the metal in order to suppress the internal stresses that are created during solidification (typically 250 – 350°C).</td>
</tr>
<tr>
<td><strong>Homogenizing</strong></td>
<td>Treatment which is performed before hot rolling which aims to suppress the microsegregation of the casting structure (typically 450 – 610°C, 10 – 48h). Also used to precipitate phases called dispersoids (grain control during conversion stages).</td>
</tr>
<tr>
<td><strong>Re-Heating</strong></td>
<td>Treatment which is performed before hot rolling which only aims to heat the metal to allow hot deformation (typically 450 – 530°C). Sometimes this treatment is mixed up with homogenizing.</td>
</tr>
</tbody>
</table>
Homogenization reduces the amount of soluble particles and gives a more uniform chemistry.

Phases after casting

- Formed from alloying elements (Cu, Mg, etc.)
- Form at high temperature after solidification or after hot working
- Can be removed by re-heating to high temperature (homogenization and/or solution heat treatment)

Nature

Phases after homogenization

- Soluble phases are brittle
  - Harmful to fatigue, toughness, crack propagation properties…
- Soluble phases remove alloying elements that strengthen the material

Role (generally harmful...)

High temperature heat treatment (450°C to 610°C)
Aluminium production goes through series of mechanical and heat treatments that all contribute to final properties.
Hot Rolling forms the material into a plate or sheet

- Forms the material to near final shape
- Some of the mechanical behavior of the product is controlled by this step
Rolling creates thin elongated grains

Dispersoids are intentionally formed in the material at high temperature prior to rolling
- Maintains a fibered grain structure
- Formed from elements such as Zr, Cr, Mn, Sc

During rolling process, the grains extend in length in one direction – an element preventing recrystallization maintains this fiber structure after the dissolution annealing process.
Extrusion forms complex shapes

- Hollow cross-sections are possible with extrusion

Main process settings:
- Billet T°
- Extrudate speed (hydraulic pump flow)
- Hydraulic pressure
- Extrudate temperature at press exit

Main process measurements:
Wrought alloys / Hardening process

Non heat-treatable alloys
- Dislocation movement prevented/slowed down by...
- Alloys strengthened by strain hardening
  - AA1000
  - AA3000 (+Mn)
  - AA5000 (+Mg)

Heat-treatable alloys
(Age hardening)
- Precipitation
- Alloys strengthened by precipitation
  - AA2000 (+Cu, Mg)
  - AA6000 (+Si, Mg)
  - AA7000 (+Zn, Mg)
Cold rolling strengthens the material and continues the forming

- To reach final thickness
- To flatten the sheet
- To harden the material
  - Intermediate annealing is carried out when needed
Heat-treatable alloys: strain hardening during cold rolling

- Grains are elongated during cold rolling + dislocations are created
  - Strength increases *(strain hardening)*

Strength vs. (E-e)/E graph

- E19
- E18
- E16
- E14
- E12
- E0

![Diagram showing grain elongation and strain hardening](image)
Illustration: dislocations observed by TEM

Illustration: Dislocation observed by Transmission Electronic Microscopy

Annealed metal

Work hardened metal

Highly work hardened metal
Intermediate annealing

- In order to soften it, the metal is heat treated (annealed)
Aluminium production goes through series of mechanical and heat treatments that all contribute to final properties.

For heat treatable alloys, additional steps are required to get the final properties.
Heat Treatments after deformation are used to increase strength

Solutionizing
- A treatment which is carried out after deformation and which aims to dissolve the precipitates that have formed during the previous stages (casting → rolling). Alloying elements go into solid solution.

Quenching
- Immediately follows solutionizing; rapid cooling of the product in order to keep the solutionized microstructure.

Natural ageing
- Metal spontaneous evolution after quenching: a small precipitation forms at room temperature and the metal hardens.

Ageing
- Heat treatment carried out at T<230°C and which leads to a very small precipitation forming (a few nm).
Strength is imparted by solutionizing, quenching, stretching, and ageing

- Hardening due to the formation of small particles (nanometer scale), which form at elevated temperature and impede dislocation motion

**Alloys 2000 / 6000 / 7000**

- Solutionizing
- Quenching
- Mechanical stress-relieving
- Natural ageing
- Artificial Aging

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*Image* via Constellium
Solutionizing and quenching

Initial state at room T°C: solid solution + Al₂Cu (equilibrium)

Example: 2024 (Al-4%Cu)

Solutionizing T°C interval

Liquid

Solid Solution

Liquid + solid

Solid Solution + Al₂Cu

Quench

After solutionizing
Solutionizing and quenching

Example: 2024 (Al-4%Cu)

As hot-rolled

After solutionizing and quench
Effect of quench rate

- Immersion water 20°C
- Immersion water 60°C
- Spray Q
- Forced air
- Air (calm)

Temperature vs. Time diagram:
- Solutionizing at 490°C
- Quench at 20°C
- Aging
- Stretching

TYS = 616 MPa (water 20°C)
TYS = 402 MPa (air)
Stretching reduces residual stress after quenching

- Relieves residual stress after quenching
- Straightens the product
- For 2XXX, stretching improves properties after heat treatment
- For 7XXX, stretching can degrade properties after heat treatment
  - High stretch is to be avoided for 7XXX
Ageing greatly increases strength

Material held at high temperature (100 – 200°C) to increase strength
Precipitates have various shapes and sizes, which control the material properties.

- Nanometer scale precipitates tremendously increase the strength of Aluminum.
- The T1 phase in Al-Cu-Li alloys is the most efficient strengthening precipitate known in Aluminum alloys.

**δ’ (Al₃Li) spheres**

**T₁ (Al₂CuLi) Hexagonal**

**θ’ (Al₂Cu) Tetragonal**

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Aging: why is there a maximum strength (peak)?
Age Hardenable Alloys

- Interactions between precipitates and dislocations
  - When a dislocation line meets a precipitate:
    - Two possibilities:
      - Shearing
      - Bowing
Age Hardenable Alloys

- Strengthening rules:

  - Shearing: \[ \Delta \tau = K f_v^{1/2} r^{1/2} \]
  - Bowing: \[ \Delta \tau = K f_v^{1/2} \frac{1}{r} \]

  \( f_v \) Precipitate volume fraction
  \( r \) Precipitate radius

- Consequence:
  - There is an optimal size for strengthening called the **critical radius**
  - It corresponds to the maximum strengthening potential (**peak strength**)
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      IV-2a Automotive

      IV-2b Aerospace

      IV-2c Packaging
Lightweighting is a key driver for material development

- **Aerospace products:**
  - To reduce fuel consumption
  - To increase payload

- **Automotive products:**
  - To reduce fuel consumption and thus CO2 emission (legislation)

- **Packaging**
  - To reduce fuel consumption and thus CO2 emission
The acceptable cost for weight reduction drives the kinds of materials and processes that can be considered.

- Even within the automotive applications, there are several lightweighting targets and acceptable costs considering all market segments.
Loading, material properties, microstructure, and processing are interrelated.
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Aluminum in cars

- Aluminum sheet, extrusions and castings increasingly used throughout the car

**Power-train**
- Engine
- Fuel tank
- Heat Exchangers
- Heat Shields
- Transmission and Driveline

**Body-in-White (structure and hang-ons)**
- Body-structure
- Hang-ons and closures (doors, hood, decklid)
- Crash management system

**Chassis & suspension**
- Subframe
- Suspension
- Wheels
- Steering system
- Brake system
Four types of applications for BiW with different needs and alloy requirements

- **Sheets** for skin, inners & structure, **extrusion** for reinforcements & structure

**Skin/Outers**
- Main need: **Perfect Surface & Complex forming**
- Alloy requirements: **Formability & Surface**

**Structure (Front & Rear)**
- Main need: **Energy absorption in crash**
- Alloy requirements: **Strength & Ductility**

**Closure Inners**
- Main need: **Stiffness & Complex forming**
- Alloy requirements: **Formability**

**Structure (Passenger Cell)**
- Main need: **Structural integrity**
- Alloy requirements: **Strength**
Hood represent the first and more mature automotive market

- Weight saving in the front end compared to steel
- 50% weight decrease at 3-4€/kg saved
- 10kg saved for less than 30€ possible

Source: Renault

120kg saved
↔ 0.5l / 100km
↔ 13g CO₂/km

47% weight saving
50% weight saving
58% weight saving

Source: Renault
Significant weight saving can be achieved using aluminium rather than steel

Mercedes S-class

Weight = 7.4kg
Aluminium Fenders
-2.4 Kg

Weight = 21.8kg
Aluminium Hood
-7.6 Kg

Weight = 18.6kg
Al-Hybrid Front-end
-2.5 Kg

Weight = 62.0kg
Aluminium Doors
-23.7 Kg

Weight = 7.6 Kg
Al-Hybrid Rear-end
-1.7 Kg

Weight 15.1kg
Aluminium Decklid
-6.2 Kg

Total = -44.1 kg

Source: DaimlerChrysler
Illustration of the link between properties, microstructure and process: ROPING

Surface aspect particularly important on parts like hoods

Stamped aluminium hood sanded with a stone to reveal the defect
Roping is a surface defect visible on formed sheets due to roughness development during forming

- Lines of roughness parallel to the rolling direction,
- Intensity of the defect proportional to plastic strain in TD,
- Roughness profile of μm amplitude and mm wavelength,
- Can be visible on the final part after painting,
- Unacceptable for outer panels.

Roughness map obtained by profilometry
Roping is due to differences in grain size and orientations.

- Coarse grains formed during hot rolling
- Giving colonies of small recrystallized grains with similar crystallographic orientations in alternate bands (Cube and Goss).
- All the grains of a colony behave similarly during straining.

Lab sample stretched 15% (TD) and sanded

EBSD orientations maps

Optical microscopy of final grain structure
Anti-roping routes of sheets for outer panels

Two main anti-roping strategies

- Avoid coarse grain formation (recrystallization) during hot rolling
  - Play on reversible hot rolling parameters and dispersoids size and volume fraction (= tune composition and homogeneization)
- Weaken orientation heredity through multiple recrystallizations
  - Add an intermediate annealing during cold rolling

Microstructures after hot rolling

Various rolling temperatures

6xxx alloy with reX during cold rolling

6xxx alloy w/o reX during cold rolling
Illustration of the link between properties, microstructure and process: Hemming ability

- Outer sheet must bend on sharp radii (typically r/t=0.5) even after significant prestrain due to previous stamping operation

| 4 samples @ 7% | 4 samples @ 9% | 4 samples @ 11% | 4 samples @ 13% | 4 samples @ 15% |

Strain limit > 9%

16013-111 SL
Strain localization and voiding at particles leads to cracking

Optical micrograph of cross section showing strain localization after 3-point bending

SEM micrograph of cross section showing crack propagation by coalescing voids around intermetallic particles

Damage / voiding around coarse Fe-containing intermetallic particles
Hemming formability:
Schematic model of cracking by bending

- Strain localization in shear bands
- Ductile fracture with nucleation, growth, and coalescence of voids

Source: Asano et al., Materials Science Forums Vols.519-521 (2006), PP. 771-776
Failure mechanisms during hemming are affected by microstructure

- Strain localization / shear instability
  - Flow stress and work hardening rate (solute content Mg/Si)
  - Crystallographic Texture
  - Grain size and dispersoïds distribution (eutectic/peritectic)

- Nucleation of voids at inclusions
  - Inclusions size
  - Yield stress

- Growth of voids
  - Plastic behavior of the matrix (work hardening and SRS)

- Coalescence of voids
  - Inclusions volume fraction

- Grain boundaries decohesion
  - Grain boundary precipitation / quench rate
Hemming formability: Influence of texture on strain localization

- Certain orientations are more prone to strain localization
- A high content of Cube orientation is beneficial for hemming ability

Optical x-section after three point bending

CP Finite Element Modeling from Ikawa et al, Mat Sci Eng A 520 (2011) 4050-4054
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Each part of the aircraft experiences different loading conditions which require different material properties:

- **Upper wing**
  - Compression strength

- **Upper fuselage**
  - Fatigue crack propagation
  - Residual strength

- **Nose**
  - Bird strike resistance (impact)

- **Vertical stabilizer**
  - Static strength
  - Shearing

- **Lower fuselage**
  - Static strength (buckling resistance)
  - Corrosion resistance

- **Lower wing**
  - Damage tolerance
  - Tensile strength
Material properties are often a compromise between strength and damage tolerance (crack resistance)

- **Damage tolerance**: the ability to withstand complete failure if material has pre-existing damage
- Damage tolerance is especially important for tensile loading (e.g. lower wing or upper fuselage)
Wing loading is different on top vs. the bottom

- The wings support the entire aircraft in flight (bending upwards)
- **Compressive strength** is important for upper wing
- **Tensile strength** and **damage tolerance** are important for lower wing
Wing loading is different in flight vs. on the ground

Spectrum Fatigue

- **Fatigue**: load varies with time
- Fatigue is variable, depending on whether the airplane is flying or on the ground
- Fatigue behaviour is **dominated by the in flight loading**
Wing = skins + spars + ribs + stringers

Rib:
- buckling
- shape

Stringer:
- Inertia
- Damage tolerance

Spar
- Stiffness

Thickness of the skin: 15-40 mm

Wing is also a fuel tank
Fuselage loading is opposite to that of the wing on top vs. the bottom

- The fuselage bows downward due to gravity
- Upper fuselage is under tension (tensile strength and damage tolerance)
- Lower fuselage is under compression (compressive strength)

Upper fuselage skin
- High damage tolerance
- Medium strength

Frames (machined or forged)
- Strength
- Damage tolerance
- Balanced properties to match the skin

Lower fuselage skin
- Compression strength (buckling)
- Corrosion resistance

Fuselage stringers
- Strength

Tensile Stress due to pressurization
Damage Tolerance
Fuselage

A380
Fuselage
Compositions and tempers are major drivers to adapt properties

- Addition of Li to 2xxx improves many critical properties for aerospace vs. conventional alloys
  - Density
  - Young's modulus
  - Corrosion resistance
  - TYS/KIC balance
  - Fatigue performance

2xxx T3 (Al-Cu-Mg)

7xxx T7

7xxx (T6 → T74) alloys for strength

2xxx + Li

7xxx T6 (Al-Zn-Cu-Mg)

Damage tolerance

strength

Warner, 2006

TYS (MPa) L-T

KIC (MPa Vm) L-T

2xxx + Li

2050, possible balances (100mm)

7050 T7451, typical (100mm)

Constellium
Compositions and tempers are major drivers to adapt properties

- Example of 7xxx alloys

<table>
<thead>
<tr>
<th>Property</th>
<th>T6 for strength</th>
<th>Corrosion resistance</th>
<th>Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T74</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example of 7150 plate:
- 7150 T6 Upper wing skin
- 7050 T76 Ribs
- 7050 T74 Spars
Minor alloying elements can have a major impact on microstructure and properties.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Ti</th>
<th>Zr</th>
<th>Sc</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x24 Mn</td>
<td>&lt;0.08</td>
<td>&lt;0.08</td>
<td>4.1</td>
<td>0.4</td>
<td>1.4</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2x24 Zr</td>
<td>&lt;0.08</td>
<td>&lt;0.08</td>
<td>3.8</td>
<td>&lt;0.05</td>
<td>1.4</td>
<td>0.02</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>2x24 Zr+Sc</td>
<td>&lt;0.08</td>
<td>&lt;0.08</td>
<td>3.8</td>
<td>&lt;0.05</td>
<td>1.4</td>
<td>0.02</td>
<td>0.11</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Warner, 2006
For 2xxx alloys + Li, aging kinetics is accelerated by prior stetch

- In addition to flatness, stretching after quench favors an homogeneous and faster precipitation

Outline

I. History of aluminium

II. Overview of Aluminium properties vs. other materials

III. Aluminium transformation schedule

IV. Lightweighting as a driver for material development

   IV-1 Overview

   IV-2 Examples of the link between customer need - properties- microstructure and process

      IV-2a Automotive

      IV-2b Aerospace

      IV-2c Packaging
Aluminum in packaging: Lightweighting, corrosion resistance and visual aspect

- **Beverage cans** (body, end & tab)
  - Largest tonnage delivered by Constellium

**Diagram:**
- Body
- End
- Tab

**Images:**
- Food cans
- Closures for glass bottles
- Cosmetic applications
- Foilstock
Aluminum vs. steel beverage cans

- 90% of the world’s beverage cans are made of aluminum (100% in the US)
- Nearly all beverage cans in North America and Europe are 2-piece (some 3-piece steel cans in China and South East Asia)
- Ends are always made of aluminum

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>Steel</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>33cl unit weight</td>
<td>12 – 14g</td>
<td>20 – 24g</td>
<td>200 – 250g</td>
</tr>
<tr>
<td>Recycling rate</td>
<td>70%</td>
<td>74%</td>
<td>70%</td>
</tr>
<tr>
<td>“Melting” point</td>
<td>700°C</td>
<td>1,500°C</td>
<td>1,200°C</td>
</tr>
</tbody>
</table>

Recently some aluminum cans have been produced just below 12g in 33cl

To check if the can body is magnetic is the only way to distinguish Al to steel cans.

Figures for EU
Can fabrication involves many steps and requires a very high production rate

Main steps from coil to can body

- **Cupper** (cup drawing)

- A plant typically produces 4 millions cups per day

**Bodymaker**

- Redrawing
- **1st ironing**
- **2nd ironing**
- **3rd ironing + bottom forming**

<table>
<thead>
<tr>
<th>Ironing Type</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cupper</td>
<td>1.56</td>
</tr>
<tr>
<td>Redraw</td>
<td>1.35</td>
</tr>
<tr>
<td>1st ironing</td>
<td>29%</td>
</tr>
<tr>
<td>2nd ironing</td>
<td>38%</td>
</tr>
<tr>
<td>3rd ironing</td>
<td>41%</td>
</tr>
<tr>
<td>Global ironing</td>
<td>66%</td>
</tr>
</tbody>
</table>

**Final can body operations**

- Trimming
- Neck forming
- Bottom reforming
Axial load resistance of can body → Yield-stress

Customer needs

**Axial load resistance** of the can body
- Process: no damage during palletization
- Process: no damage during can filling with beverage
- In-service: can resistance

Alloy solution:
- Increase in-service strength
- After drawing, ironing, varnish curing and ageing

Design solution:
- Adapt thickness
Almost no tear-offs when ironing → Formability & high casting quality

Customer needs
- Efficient bodymaking process
  - Minimization of production stops due to tear-offs

- High formable alloy: 3104
- High casting quality with small & rare inclusions
  → Linked to preferential grain orientations (crystallographic texture)

Can body stock = 0.26mm
Can mid-wall = 90µm
Easy opening end with buckling resistance

→ Strength and corrosion resistance

**Part specifications**

- Stiffness
- **No underscore corrosion**
- Buckling resistance
- Visual aspect
- Forming

- **Good corrosion resistance**
  Which is the case for 5182 with appropriated varnishes
Limit material waste when trimming: avoid earing

Customer need
- Efficient process without material waste when trimming

- Earing should be lower than 7% of the cup

Earing = $\frac{(h_v - h_p)}{h_p}$

Cup drawn on 3104 final sheet
Earing profile is linked to anisotropy due to texture

**Example: calculation for Brass and Cu orientations**
Earing profile is linked to anisotropy due to texture

- An optimum texture can be found controlling recrystallization

![Graph showing texture types](image)
Homogenization is a key step for earing control

- Nucleation of new grains on dispersoids and intermetallic particles
- Grain growth in PFZ
- Dispersoids hinder GB

Microstructure after hot rolling