Aluminium and its alloys
Alumina raw materials

Alumina can be processed from bauxite, kaolinite and nepheline

- **Bauxite**
  - 30-50% Alumina \( (\text{Al}_2\text{O}_3) \)
  - 3-13% Silica \( (\text{SiO}_2) \)
  - 10-18% Titanium oxide \( (\text{TiO}_2) \)
  - Balanced water \( (\text{H}_2\text{O}) \)

- **Kaolinite**
  - 30-32% Alumina \( (\text{Al}_2\text{O}_3) \)
  - Balanced Silica \( (\text{SiO}_2) \) and water \( (\text{H}_2\text{O}) \)

- **Nepheline**
  - 30% Alumina \( (\text{Al}_2\text{O}_3) \)
  - 40% Silica \( (\text{SiO}_2) \)
  - 20% \( \text{Na}_2\text{O} + \text{K}_2\text{O} \)
Bayer Process

Mining
- Bauxite
  - Crushing
  - Washing
  - Drying

Refining
- Digestion
  - Decomposition
  - Calcination
  - Alumina

Smelting
- Casting
  - Primary Aluminium
  - Recasting Rolling Extruding
  - Finished Products
Bayer Process

- Bauxite is washed ground and dissolved in caustic soda (NaOH) at high pressure and temperature.
- Sodium aluminate solution containing nonsoluble bauxite residues sink to the bottom 'red mud'.
- Seeding agent is added to the clear sodium aluminate solution to give alumina precipitates.
- Precipitates are passed through a rotary kiln for calcination at ~1100 °C to give white powder of pure alumina.
(Aluminium smelting/electrolysis)

Feed Material: Alumina (Al₂O₃)
Electrolyte: Cryolite (Na₃AlF₆)
Anode material: Carbon
Cathode material: Carbon/graphite

Anode: \(2\text{O}^{2-} \rightarrow \text{O}_2 + 4\text{e}^-\)
\[
2\text{O}^{-2} + \text{C} \rightarrow \text{CO}_2 + 4\text{e}^- 
\]
Cathode: \(\text{Al}_3^+ + 3\text{e}^- \rightarrow \text{Al}\)

Overall Rxn: \(2\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 4\text{Al} + 3\text{CO}_2\)
Hall-Hérroult process
Properties of Aluminium

- High corrosion resistance
- Excellent machining properties
- Light weight
- High thermal/electrical conductivity
- High ductility/easily deformable
Wrought Aluminium alloys

Composition of aluminium alloys are regulated by internationally agreed classifications system

- 1XXX Al of 99% minimum purity
- 2XXX Al - Cu alloys
- 3XXX Al - Mn alloys
- 4XXX Al - Si alloys
- 5XXX Al - Mg alloys
- 6XXX Al - Mg - Si alloys
- 7XXX Al - Zn - Mg alloys
- 8XXX Miscellaneous alloys, e.g. aluminium-lithium alloys
Main groups of wrought aluminium

1xxx series (Super-purity and commercial-purity aluminium)
- 3xxx series (Al-Mn and Al-Mn-Mg alloys)
- 5xxx series (Al-Mg alloys)
- 8xxx series (Miscellaneous alloys)

- 2xxx series (Al-Cu and Al-Cu-Mg alloys)
- 6xxx series (Al-Mg-Si alloys)
- 7xxx series (Al-Zn-Mg and Al-Zn-Mg-Cu alloys)
Main groups of wrought aluminium

Non-heat-treatable alloys

- 1xxx series (Super-purity and commercial-purity aluminium)
- 3xxx series (Al-Mn and Al-Mn-Mg alloys)
- 5xxx series (Al-Mg alloys)
- 8xxx series (Miscellaneous alloys)

Heat-treatable alloys

- 2xxx series (Al-Cu and Al-Cu-Mg alloys)
- 6xxx series (Al-Mg-Si alloys)
- 7xxx series (Al-Zn-Mg and Al-Zn-Mg-Cu alloys)
Aluminium alloys and temper designations

Aluminium alloy and temper designation systems (IADS system)

<table>
<thead>
<tr>
<th>4-digit series</th>
<th>Aluminium content or main alloying elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 xxx</td>
<td>99.00% minimum</td>
</tr>
<tr>
<td>2 xxx</td>
<td>Copper</td>
</tr>
<tr>
<td>3 xxx</td>
<td>Manganese</td>
</tr>
<tr>
<td>4 xxx</td>
<td>Silicon</td>
</tr>
<tr>
<td>5 xxx</td>
<td>Magnesium</td>
</tr>
<tr>
<td>6 xxx</td>
<td>Magnesium and silicon</td>
</tr>
<tr>
<td>7 xxx</td>
<td>Zinc</td>
</tr>
<tr>
<td>8 xxx</td>
<td>Others</td>
</tr>
</tbody>
</table>

- The first digit indicates the alloy group.
- The second indicates modifications to alloy or impurity limit.
- The last two identify the aluminium alloy or indicates the aluminium purity.

Temper designations (Added as suffix letters of digits to the alloy number)

<table>
<thead>
<tr>
<th>Suffix letter F, O, H, T or W</th>
<th>Indicates basic treatment or condition.</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>As-fabricated</td>
</tr>
<tr>
<td>O</td>
<td>Annealed wrought products only</td>
</tr>
<tr>
<td>H</td>
<td>Cold-worked (strain hardening)</td>
</tr>
<tr>
<td>T</td>
<td>Heat treated (stable)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>First suffix digit</th>
<th>Indicates secondary treatment used to influence properties*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cold worked only</td>
</tr>
<tr>
<td>2</td>
<td>Cold worked and partially annealed</td>
</tr>
<tr>
<td>3</td>
<td>Cold worked and stabilized</td>
</tr>
<tr>
<td>4</td>
<td>Partial solution plus natural ageing</td>
</tr>
<tr>
<td>5</td>
<td>Annealed cast products only</td>
</tr>
<tr>
<td>6</td>
<td>Solution plus cold work</td>
</tr>
<tr>
<td>7</td>
<td>Solution plus natural ageing</td>
</tr>
<tr>
<td>8</td>
<td>Artificially aged only</td>
</tr>
<tr>
<td>9</td>
<td>Solution plus artificial ageing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second suffix digit</th>
<th>Indicates residual hardening*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 Hard</td>
<td></td>
</tr>
<tr>
<td>1/2 Hard</td>
<td></td>
</tr>
<tr>
<td>3/4 Hard</td>
<td></td>
</tr>
<tr>
<td>Hard</td>
<td></td>
</tr>
<tr>
<td>Extra hard</td>
<td></td>
</tr>
</tbody>
</table>

*Where a second digit is used for T tempers, or a third is used for condition H, this indicates a specific treatment, e.g. amount of cold work to secure specific properties.

Examples of alloy and temper descriptions:
1) 5152 H36 = Aluminium-magnesium alloy, cold worked and stabilised to develop a 1/4 hard condition
2) 6061 T6 = Aluminium – magnesium – silicon alloy, solution heat treated followed by artificial ageing.
Properties and applications wrought Al alloys

1xxx series

Properties:
- Low tensile strength (90 MPa)
- Yield stress of 7-11 MPa.

Applications:
- Electrical conductors
- Chemical process equipment
- Foils
- Decorative finishes
- Capacitor (by panasonic)
Properties and applications wrought Al alloys

2xxx series

Properties:
- High strength (2119: $\sigma_{TS} 505$ MPa).
- Good creep strength at high temp.
- High toughness at cryogenic temp.
- Good machinability.

Applications:
- Welding wires
- Fuel Tanks
- Aircraft body
Properties and applications wrought Al alloys

3xxx series

Al-Mn alloys (upto 1.25% Mn)
Greater amount leads to large primary Al6Mn particles
deleterious local ductility)

Properties:
- Moderate strength, i.e., $\sigma_{TS} \sim 110 \text{ MPa}$ in annealed 3003
- High ductility
- Excellent corrosion resistance

Applications:
- Foil
- Roofing sheet

Al-Mn-Mg alloys
(provide solid solution strengthening)
and widely used in a variety of strain hardened tempers

Properties:
- Moderate strength, i.e., $\sigma_{TS} \sim 180 \text{ MPa}$ in annealed 3004.
- Readily fabricated
- Excellent corrosion resistance

Applications:
- Manufacturing beverage cans
Properties and applications wrought Al alloys

4xxx series
Aluminum / Silicon alloys (Silicon ranging from 0.6% to 21.5%)

Properties:
- Excellent weldability and fair weld strength of 120 MPa
- Moderate strength
- Has heat and non-heat-treatable properties
- Excellent corrosion resistance

Applications:
- Used as filler material
- Welding and brazing wire
- Forged engine pistons

Main application: Architectural applications
Properties and applications wrought Al alloys

5xxx series

Properties:
- Al-0.8Mg (5005): σ_y 40 MPa, σ_TS 125 MPa
- Al-(4.7-5.5)Mg (5456): σ_y 160, σ_TS 310 MPa
- High rate of work hardening
- High corrosion resistance
- Bright surface finish

Applications:
- Transportation structural plates
- Large tanks for petrol, milk, grain
- Pressure vessel
- Architectural components
Properties and applications wrought Al alloys

6xxx series

Properties:
- Medium-strength structural alloys (most widely used 6063-T6, $\sigma_y$ 215 MPa, $\sigma_{TS}$ 245)
- Higher strength on ageing, 6013 - Al-Mg-Si-Cu, $\sigma_y$ 330 MPa(T6) and 415 (MPa) T8.

Applications:
- Transportation structural plates
- Large tanks for petrol, milk, grain
- Pressure vessel
- Architectural components
Properties and applications wrought Al alloys

6xxx series
Properties and applications wrought Al alloys

7xxx series

Properties:
- Strength is insensitive to cooling rate hence suitable for welding
- Yield strength might be double to Al-Mg and Al-Mg-Si alloys (~ upto 600 MPa)
- Stress corrosion cracking resistance in Al-Zn-Mg-Cu alloys

Applications:
- Light weight military bridge
- Aircraft construction
Properties and applications wrought Al alloys

8xxx series

Properties:
- High corrosion resistance at high temp & pressure
- Deep drawing

Applications:
- Al-1.1Ni-0.6Fr (8001) - nuclear energy installations
- Al-0.75Fe-0.7Si (8011) - bottle caps.
- Al-Sn (up to 7%) soft bearings
- Al-Li for aerospace applications
Designations of cast aluminium alloys

United States Aluminium Association system (Using four-digit system)

- **1xx.x** Al, 99.00% or greater Al alloys grouped by major alloying elements
- **2xx.x** Cu
- **3xx.x** Si with added Cu and/or Mg
- **4xx.x** Si
- **5xx.x** Mg
- **7xx.x** Zn
- **8xx.x** Sn
- **9xx.x** Other elements
- **6xx.x** Unused series

**1xx.x series**
- Second two digits indicate the minimum percentage of Al, Eg: 150.x = 99.50% Al.
- Last digit (after decimal point) indicates product forms. 1 = casting, 2 = ingot

**2xx.x to 9xx.x series**
- Second two digits identify the different aluminium alloys
- Last digit (after decimal point) indicates product forms
Cast aluminium alloys

Properties required for good casting
- Low melting temperature
- Low solubility of gases except H2
- Good fluidity
- Good surface finishes

Main disadvantage
- High solidification shrinkage (3.5-8.5%)

Factors controlling properties
- Melting and pouring practices
- Impurity levels
- Grain size
- Solidification rate

Cast aluminium alloys are widely used for transport applications, Eg: Cast engine block
Strengthening Mechanism of Metals
(Solid Solution Strengthening)

Adding other elements in solid solution

Mechanism:
- Dissolved impurities distort lattice by
  
  **Substitutional / Interstitial**
  
  - strengthening effect increases as
  
    $|\Delta r| \uparrow$ ($\Delta r = \rho_{\text{host}} - \rho_{\text{impurity}}$)
  
  - The stress generated can produce a barrier to dislocation motion
Strengthening Mechanism of Metals
(Precipitation(Age Hardening)/dispersion hardening)

Adding second phase particles or precipitation of supersaturated solid solution

Mechanism:
- dislocation movement is impeded across grain boundaries between different phases

- Example is Al-4%Cu alloy

Al$_2$Cu$_3$ precipitates at grain boundaries

Al$_3$Li precipitates
Strengthening Mechanism of Metals
(Strengthening by Grain Size Reduction)

Strengthening by reduction in grain size

Mechanism:
In general, slip across grain boundary involves
- Discontinuity of slip planes
- Change in slip direction
- For many materials, the yield strength increases with a decrease in grain size

- The yield strength and the grain size are related by the Hall-Petch Equation

\[
\sigma_{\text{yield}} = \sigma_0 + k_y d^{-1/2}
\]
Strengthening Mechanism of Metals
(Strain Hardening)

Cold work (strengthening by low-temperature plastic deformation)

Mechanism:
- Plastic deformation creates dislocations
- Upon repeated or extensive deformation, dislocations multiply, move, and (on average) repel each other thereby decreasing dislocation mobility
- This increases the yield strength and the ultimate tensile strength