Recent development in aluminum alloys
### Pure Aluminium

**Annealed pure aluminium is:**
- not very strong
- soft and ductile
- light in weight
- corrosion resistant
- of high thermal and electrical conductivities

**Typical mechanical properties are:**

<table>
<thead>
<tr>
<th></th>
<th>Annealed</th>
<th>Moderate cold work</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% Yield Strength</td>
<td>15 MPa</td>
<td>50 MPa</td>
</tr>
<tr>
<td>UTS</td>
<td>50 MPa</td>
<td>100 MPa</td>
</tr>
<tr>
<td>Elongation †</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Hardness</td>
<td>130 Hv</td>
<td>230 Hv</td>
</tr>
</tbody>
</table>

† maximum elongation before breaking

Some characteristics of pure aluminium
Values in millions of metric tonnes.
Values might not add up due to rounding.
1. Skimmings, scalpings, sawings
2. Not taken into account in statistics
3. Such as powder, paste and deoxidation aluminium
4. Area of current research to identify final aluminium destination (reuse, recycling or landfill)
Figure 1: Global Al consumption, production, recycling and the vehicle share of the Al market.
Sheet AI cars

1916 Premier

1931 Dusenberg

1948 Tasco

1947 Dyna Panhard
**Wrought, heat-treatable aluminium alloys**

- **Al - Cu**
  - Pb and Bi (both insoluble in Al) added to improve machinability
  - Mg and Zn added to improve strength
  - Ni and Fe added to form intermetallic which inhibits recrystallisation and grain growth
- **Al - Mg - Si**
  - Cu added to offset delayed ageing effect
  - Cr added to enhance corrosion properties
  - Excess Si added to enhance tensile properties
- **Al - Zn - Mg**
  - Cu added to obtain very high strength

Alloying elements which confer:
- High strength
- Strength, ductility and toughness
- Higher modulus and lighter weight
- Other special properties

Alloying elements which confer:
- High strength
- Ductility and toughness

Special alloying elements which confer:
- High strength
- Ductility and toughness

Zn, Cu, Mn, Mg, Si, Fe, Li, Pb, Bi, Ni, Cr, B, Ti
Wrought aluminium alloy compositions

Alloying element concentrations (wt%)

AA alloy designation

- 7129
- 7003
- 6111
- 6061
- 5182
- 4147
- 3003
- 2036
- 1100

Mg
Mn
Fe
Si
Cu
Zn
Cast aluminium alloy compositions

Alloying element concentrations (wt%)

Fe
Si
Cu
Zn

AA alloy designation

390
380
319
356

Alloying element concentrations (wt%)

0 2 4 6 8 10 12 14 16 18 20 22 24
<table>
<thead>
<tr>
<th>AA Alloy</th>
<th>Si</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Zn</th>
<th>Fe</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transportation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A319.0</td>
<td>6.5</td>
<td>4.0</td>
<td>0.1</td>
<td>0.5</td>
<td>3.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>356.0</td>
<td>7.5</td>
<td>0.25</td>
<td>0.45</td>
<td>0.35</td>
<td>0.35</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>A356.2</td>
<td>7.5</td>
<td>0.1</td>
<td>0.45</td>
<td>0.005</td>
<td>0.005</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>380.0**</td>
<td>9.5</td>
<td>4.0</td>
<td>0.1</td>
<td>0.5</td>
<td>3.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>384.0**</td>
<td>12.0</td>
<td>4.5</td>
<td>0.1</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>Ni 0.5</td>
</tr>
<tr>
<td>390.0</td>
<td>18.0</td>
<td>5.0</td>
<td>0.65</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1100</td>
<td>0.5</td>
<td>0.2</td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>3003</td>
<td>0.6</td>
<td>0.2</td>
<td></td>
<td>1.5</td>
<td>0.1</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>4032</td>
<td>13.5</td>
<td>1.3</td>
<td>1.3</td>
<td></td>
<td>0.25</td>
<td>1</td>
<td>Ni 1.3</td>
</tr>
<tr>
<td>5052</td>
<td>0.25</td>
<td>0.1</td>
<td>2.8</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>5454</td>
<td>0.25</td>
<td>0.2</td>
<td>3.0</td>
<td>1.0</td>
<td>0.25</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>5754</td>
<td>0.4</td>
<td>0.1</td>
<td>3.6</td>
<td>0.5</td>
<td>0.2</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>5182</td>
<td>0.2</td>
<td>0.15</td>
<td>5.0</td>
<td>0.5</td>
<td>0.25</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>6008</td>
<td>0.9</td>
<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
<td>0.2</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>6060</td>
<td>0.6</td>
<td>0.1</td>
<td>0.6</td>
<td>0.1</td>
<td>0.15</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>6061</td>
<td>0.8</td>
<td>0.4</td>
<td>1.2</td>
<td>0.15</td>
<td>0.25</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>6022</td>
<td>1.5</td>
<td>0.11</td>
<td>0.7</td>
<td>0.1</td>
<td>0.25</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>6111</td>
<td>1.1</td>
<td>0.9</td>
<td>1.0</td>
<td>0.45</td>
<td>0.15</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>6181A</td>
<td>1.1</td>
<td>0.25</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>6016</td>
<td>1.5</td>
<td>0.2</td>
<td>0.6</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>6082</td>
<td>1.3</td>
<td>0.1</td>
<td>1.2</td>
<td>1.0</td>
<td>0.2</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>7003</td>
<td>0.3</td>
<td>0.2</td>
<td>1.0</td>
<td>0.3</td>
<td>6.5</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>7108</td>
<td>0.1</td>
<td>1.4</td>
<td></td>
<td></td>
<td>5.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td><strong>EN AC-51400DF</strong></td>
<td>2</td>
<td>5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| **Packaging** |      |      |      |      |      |      |       |
| 3004/3104**   | 0.6  | 0.25 | 1.3  | 1.5  | 0.25 | 0.8  |       |

| **Building products** |      |      |      |      |      |      |       |
| 3105**        | 0.6  | 0.3  | 0.8  | 0.8  | 0.4  | 0.7  |       |

*http://www.matweb.com; **secondary alloys
typical manufacturing scheme for AA6XXX body sheet

DC Casting
- scalping & homogenization
- tandem hot-rolling
- break-down mill
- cold-rolling

Twin-Roll Casting
- $t = 5 - 6 \text{ mm}$
- cold-rolling

solutionizing $> 530 ^\circ C$
- quenching
- T4 (T4P)
- stamping
Thin-gauge wide strip casting
DIAGRAMS OF GP ZONES

Al - Cu
(a) Platelet on (100) cube plane

Al - Zn
(b) Sphere

Al - Mg$_2$Si
(c) Rod along [100] direction

GP zones in Al-Cu, Al-Zn and Al Mg$_2$Si
(a) Diagram of a section through a coherent ‘platelet’ in Al-Cu

(b) Diagram of a section through a coherent ‘sphere’ in Al-Zn

Coherency in a cubic lattice; [001] section of GP zone in Al-Cu and Al-Zn
\[ \Delta G = -V\Delta G_v + V\Delta G_s + A\gamma \]

which becomes for a spherical cluster

\[ \Delta G = -\frac{4}{3}\pi r^3(\Delta G_v - \Delta G_s) + 4\pi r^2\gamma \]

and

\[ \Delta G_{\text{critical}} = \frac{16\pi \gamma^2}{3(\Delta G_v - \Delta G_s)^2} \]

\[ r_{\text{critical}} = \frac{2\gamma}{(\Delta G_v - \Delta G_s)} \]

Free energy change on solute cluster formation (\(\Delta G\))

- \(A\gamma \propto r^2\)
- \(\Delta G_{\text{critical}}\)
- \(r_{\text{critical}}\)
- \(V(\Delta G_v - \Delta G_s) \propto r^3\)

Radius of solute cluster (\(r\))

Homogeneous nucleation of a solute cluster

TALAT

1204.03.09
Dislocation
GP zones surrounded by strain fields

Slip direction

Dislocation

GP zone surrounded by strain field
Dislocation loop

(a)

(b)
Shape of an ageing curve is determined by:
(a) the alloy composition
(b) the quench rate
(c) the ageing temperature
(d) the nucleation rate
(e) the growth rate
(f) the rate of coarsening
(g) the precipitation sequence

Precipitate (cluster) nucleation rate \( (N) \) is given by:

\[ N = A \exp\left(-\frac{Q}{kT}\right) \exp\left(-\frac{\Delta G_{\text{critical}}}{kT}\right) \]

where
A is a constant
Q is the activation energy for diffusion

TALAT
Typical ageing curves
1204.03.15
Grain boundary Precipitate-free Zone - solute depletion

Solute concentration (wt. % Zn)

Distance d (nm) from the grain boundary

- C1 (120°C)
- C2 (140°C)
- C3 (160°C)
- C4 (180°C)

Direct quench into oil

Aged at 120°C for 2 hours

Aged at 140°C for 2 hours

Aged at 150°C for 1.5 hours

Grain boundary Precipitate-free Zones - vacancy depletion: Al-17.5% Zn

Vacancy concentration

Quenching Temperature

Critical vacancy concentration

Equilibrium vacancy concentration

High

Medium

Low

Distance from grain boundary
Al - 1.2% Mg₂Si: Heterogeneous precipitation on dislocations. Quenched to 250°C and held for 10 minutes + 6 months at room temperature + 24 hours at 160°C.

Note the region free of precipitates adjacent to the dislocation.

dislocation line + array of ‘end-on’ needle precipitates

TEM of precipitation on a dislocation + PFZ
AI - 1.2% Mg$_2$Si: Heterogeneous precipitation on dislocations. Quenched to 250°C and held for 10 minutes + 6 months at room temperature + 24 hours at 160°C.

Note the region free of precipitates adjacent to the dislocation.

dislocation line + array of ‘end-on’ needle precipitates
Liqidus surface at the aluminium-rich corner of the AlMgSi ternary phase diagram. The pseudo-binary line (also called the quasi-binary line) for Al-Mg₂Si is shown [after L E Mondolfo ref 4].
6013 alloy aged 8 hours at 165°C

TEM bright image of and corresponding diffraction pattern with [001] Al zone axis.

High resolution images of the precipitates
(a) the transition ordered phase;
(b) Q(Al\textsubscript{5}Cu\textsubscript{2}Mg\textsubscript{8}Si\textsubscript{7}) precipitate and its cross section as an insert.

The microstructures contain fine uniformly dispersed rod-shape particles elongated in the <100>Al directions having rectangular or circular cross section. The streaks along <100>Al directions are attributed to shape effect of precipitates. The identification of the phases by SADP is difficult because of the similarity of diffraction patterns from different type of phases (β’, Θ’ or S’).
Superplastic elongation of 4850% in Pb-62%Sn alloy (A) after Ahmed and Langdon 1977 and 5500% in the sample of commercial aluminium bronze (B) after Higashi et al., 1985

Overview of superplastic behavior as a function of strain rate for aluminium alloys of grain sizes from 15 µm to sub-micron. Included data points for Ni base alloys.
Superplastic Deformation of Aluminium Alloys

Optical microstructures of alloy AG2 continuously cast and hot rolled at 673K (a) and the same alloy cast to a copper mould AG2A (b)

Relationship of tensile stress versus strain rate at temperatures 623K, 673K, 723K and 773 K obtained for the alloy AG1 and AG2.