Products – Rolled products

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1 Rolled products

1.1 Sheet products for automotive applications (examples)

Rolled products as plate, sheet, foil or welded tubes are the second largest fraction of aluminium in automobile applications. They are used for many different components to reduce weight and enhance part performance.

Special alloys and tempers have been developed and are in use that provides the properties needed to meet the specific quality requirements of the various parts.

Sheet products are provided with special surface topographies, claddings as well as with pre-treatments for lubrication, joining and painting by coil coating processes.
HF-welded sheet metal tubes, hydroformed

DC Coupé aluminium sheet stampings

Radiator
DC rear axle cradle

BMW fabricated wheel
1.2 Automotive alloys are specially tailored material qualities

Aluminium alloys of the non-heat treatable Al-Mg (EN AW-5xxx series) and the heat treatable Al-Mg-Si (EN AW-6xxx series) alloy system, were especially tailored by suitable variations in chemical composition and processing for various applications, e.g.

- For use in chassis the Al-Mg alloys were optimised for optimum strength and corrosion resistance.
- In the field of carbody sheets the Al-Mg-Si alloys are frequently applied and have been improved for formability, surface appearance and age-hardening response.
1.3 Alloys

1.3.1 Special alloys and tempers for automotive use

Special alloys and tempers have been developed and are in use that provides the properties needed to meet the specific quality requirements of the various parts.

Aluminium alloys for automotive sheet application are non-heat treatable alloys:
- 1xxx series - Al 99,5
- 3xxx series - Al-Mn
- 5xxx series - Al-Mg (Mn)

Age hardenable alloys:
- 6xxx series - Al-Mg-Si
- 2xxx series - Al-Cu (not in use in Europe)
- 4xxx series - Al-Si

The latter alloys are used for braze sheet for heat exchanger applications (as clad sheet).

See following subsections for compositions of automotive sheet alloys and typical applications.

The two main body sheet alloy groups are:

a) EN 6xxx Al-Mg-Si:
   - good formability (condition "T4")
   - age hardenable (condition "T6")
   - good surface appearance
   - good corrosion resistance
   - solution annealing required >500°C

b) EN 5xxx Al-Mg-Mn:
   - good formability (condition "O")
   - good corrosion resistance (< 3% Mg; for > 3% Mg prone to intercrystalline corrosion)
   - good strain hardening (n-values)
   - stress-strain markings possible!
1.3.2 Composition

Chemical composition of selected automotive sheet alloys

See also:
- AAM – Materials – 3 Designation system > Wrought alloys > International designation systems for wrought alloys
- AAM – Products – 1 Rolled products > Tempers and mechanical properties > Typical mechanical properties of rolled products for automotive applications
- AAM – Products – 1 Rolled products > Flow curve, formability data > Forming limit diagram
- AAM – Products – 1 Rolled products > Microstructure and surface
- AAM – Products – 1 Rolled products > Corrosion resistance

<table>
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<th>Designation</th>
<th>Chemical composition (mass %), remainder Al</th>
<th>Remarks</th>
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Modifications of heat exchanger alloys 3xxx

See also:
- AAM – Applications – 1 Power train > Heat exchangers > Radiators > Engine cooling system – Water-side corrosion
- AAM – Products – 3 Automotive tubes > Corrosion properties > Long Life Alloys (LLA)

Alloy EN AW-3003 (EN AW-AlMn1Cu) is a widely used generic material for heat exchangers.

Due to various producer developments and specific user requirements there exist numerous modifications of the basic alloy 3003:
- EN AW-3102 (EN AW-AlMn0.2)
- EN AW-3103 (EN AW-AlMn1)
- EN AW-3005 (EN AW-AlMn1Mg0.5)
- EN AW-3105 (EN AW-AlMn0.5Mg0.5)
- Long Life Alloys

Users are recommended to contact their suppliers for specific information or for a suitable selection of alloys for the given purpose.
1.3.3 Typical application areas

See also:
- AAM – Materials – 3 Designation system > Wrought alloys > International designation systems for wrought alloys

(see additional comments on alloy 3003 under “Composition”)

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<th>Designation</th>
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<th>Specific Properties</th>
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<td>heat shields, structural parts</td>
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<td>high (T6) strength and good recyclability</td>
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1.4 Available forms

1.4.1 Hot rolled products

See also:
AAM – Materials – 5 Wrought materials production > Automotive sheet > From ingot to strip and panel > Hot Rolling

Sheet can be processed directly to final gauge by hot rolling. This process is very economical, but available alloys and tempers are limited. Also, dimensional tolerances - typically ± 0.30 to ± 0.40 mm - cannot match those of cold-rolled sheet.

Hot rolled products are used for many automotive applications, particularly 5xxx alloys for structural parts such as wheel stock, suspension components and body reinforcements. For details on available tolerances contact your material supplier.
1.4.2 Cold rolled products

Cold rolled products are sheet or plate, where the final gauge is processed by cold rolling. Often additional annealing treatments are necessary to adjust the properties specified by customers.

Cold rolled products are characterised by narrow tolerances on shape and dimensions. Thickness tolerances depend on the type of alloy, sheet or strip thickness range and rolling width, and are listed in standards EN 485-4.

**Example:** EN AW-5182-O, 1.10 mm thick

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1.4.3 Clad sheet

See also:
- AAM – Products – 1 Rolled products > Alloys > Composition
- AAM – Materials – 5 Wrought materials production > Automotive sheet > From ingot to strip and panel > Production of Brazing Sheet

Clad material is fabricated by rolling cladding material on one or both sides of a core material. This composite is processed to combine the properties of the core material (e.g. high strength) with that of the cladding (e.g. brazeability, surface brightness, corrosion resistance). The thickness of claddings is usually between 5 to 20% of total thickness of the composite. In automotive applications braze clad sheet is used in heat exchangers. Usually the core material is made out of 3xxx or 6xxx alloys (s. Links); 4xxx alloys are chosen for cladding. Tolerances on shape and dimensions are the same as for cold rolled products.

Figures (below): Micrographs of brazing sheet. Core alloy 3xxx clad on both sides with 4xxx alloy in different cladding thickness.

Precipitate microstructure
Source: VAW

Grain microstructure
Source: VAW
1.4.4 Surface pre-treatment

See also:
- AAM – Materials – 5 Wrought materials production > Automotive sheet > Special sheet surfaces > Chemical and electrochemical pre-treatments
- AAM – Manufacturing – 4 Surface finishing > Pre-conditioning of Al-forms > Sheet / strip > Cleaning of coil / sheet products

Many of the rolled products for automotive applications are delivered with various surface conditions, pre-treatments and pre-coatings:

- Lubricants (e.g. oil)
- Dry film lubricants (e.g. semi-dry products, hot melts, acrylate layers)
- Pre-treatments (e.g. Ti/Zr-conversation layer)
- Pre-coatings processed by coil coating (substitution of electrophoretic coating)
- Top-coatings processed by coil coating

Reasons for surface pre-treatment are e.g.:

- Surface protection during transport and handling
- Improvement of tribological conditions during forming processes
- Preparing surface for joining operation (e.g. adhesive bonding or welding)
- Reduced process chain for lean production and cost saving
1.4.5 Surface topography

See also:

- AAM – Materials – 5 Wrought materials productions > Automotive sheet > Special sheet surfaces

Typical surface topographies of sheet material are **Mill-finish** or **EDT** (Electro Discharge Texturing) surfaces. Mill-finish surfaces are strongly anisotropic. They are used in applications where the surface appearance of the formed sheets is subordinate. For applications where advanced formability and high surface appearance especially after lacquering is necessary the EDT surface is used.

Characteristic roughness values for such surfaces of autobody sheets according to SEP 1470 are:

- Mill-finish: \( R_a = 0.3\text{-}0.5\mu m \)
- EDT: \( R_a = 0.7\text{-}1.3\mu m \)
AA6016 (AlSi1.2Mg0.4) with surface topography 'EDT' (Electro Discharge Textur.)
Source: VAW
1.5 Tempers and mechanical properties

1.5.1 Introductory comments

See also:
  AAM – Products – 1 Rolled products > Alloys

Static mechanical properties

Standardised static mechanical properties of aluminium sheet alloys for automotive application are listed in standards EN 573-3. These data are statistically evaluated property data and represent guaranteed minimum properties suitable for design calculations. Users are asked to consult the relevant standards.

Typical mechanical properties are generally not listed in standards. They represent average values of production lots and refer to various semi-finished products in typical thickness dimensions. The data are intended only as a guide for comparison of Al-alloys for product development. They are not suitable for design calculations. The value of typical property data is that they represent more truly the property profile rather than a statistical minimum of both strength and ductility, which are inversely related to each other.

Fatigue Properties

Fatigue data obtained with smooth specimen testing in the form of S-N-curves are generally of little value for design, since alloy composition and type of material are of much lower influence than fabricated notches or other geometric irregularities. For orientation purposes, therefore, only endurance limits for various alloys are illustrated and as a case study smooth specimen S-N-curves for AlMg3Mn-O (EN AW-5754-O) at various R-values.
1.5.2 Typical mechanical properties of rolled products for automotive applications

See also:
- AAM – Materials – 3 Designation system > Wrought alloys > H-Temps for strain-hardening wrought alloys (EN 515)

Literature:

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2) $\sigma_{0,2}$
3) $R_m$
1.5.3 Comparison of static and fatigue strength

The figure below illustrates that the increase in unnotched fatigue strength with increasing static strength of the alloy is comparatively small and even less for notched (and welded) test pieces.

The component's life is much more affected by stress concentrations which should be avoided or minimised in design and fabrication as much as possible.
1.5.4 Fatigue – S-N-curves for AlMg3Mn (EN AW-5454)

The unnotched axial fatigue S-N-curves at right for AlMg3Mn-O are typical for medium strength aluminium alloys.

Considering that the yield strength of the material is typically 110 MPa the data show an endurance limit at $R = 0.5$ above the yield strength, demonstrating that the materials are cyclic strain hardening, i.e. it also performs in a stable manner when strain hardened by forming operations.

On the other hand, the data illustrate the well known fact that the endurable stress amplitude is sensitive to mean stress.

Most aluminium alloys suffer some reduction of fatigue strength in corrosive environments. The fatigue strengths of the corrosion-resistant alloys used for automotive sheet (1xxx, 3xxx, 5xxx, 6xxx) are less affected by corrosive environments than are high-strength alloys (2xxx, 7xxx).

![S-N-curves for AlMg3Mn-O sheet (3.5mm) for different R values](source: VAW)
1.6 Flow curves, formability data

1.6.1 Basic material data for FEM simulation of sheet forming processes

To optimise forming processes FEM-simulation is a common tool. The plastomechanical behaviour of any material is characterised by the following input-parameters:

- **Flow Curves** (FC) describe the stress as function of strain, i.e. the strain-hardening characteristics of the material
- **Anisotropy** of the material is taken into account by the directionality of yield stress (yield locus) and the relation between thickness strain and width strain (r-value)
- **Forming Limit** Diagrams (FLD) displays the range of two-dimensional strain to fracture. It helps to evaluate the FEM results.
1.6.2 Flow curve (anisotropy)

See also:
- AAM – Materials – 2 Alloy constitution > Heat treatment > Solution treatment and ageing
- AAM – Materials – 2 Alloy constitution > Strengthening mechanisms > Strengthening of aluminium alloys

The Flow Curve (FC) describes the strain-hardening of the material during deformation, determined by tensile test (see EN 10002 for sheet material).

Al-Mg-alloys (5xxx) reveal highest strain-hardening characteristics for high amounts of Mg in solid solution.

Al-Mg-Si alloys (6xxx) gain their strength mainly by precipitation hardening (see Links).

Due to anisotropy caused by strong crystallographic texture some sheet metals show different flow behaviour in different directions of the sheet.

Figure below: Yield curves of EN AW-5754-0 (EN AW-AlMg3) in different directions to the rolling direction.

Source: VAW
Figure below: Yield curves of AA 6016-T4 (AlSi1.2Mg0.4) in different directions to the rolling direction.

Source: ALCAN (Suisse)
1.6.3 Flow curve – Fitting approaches

Only relatively small strains (20-40%) are achieved until (ductile) fracture occurs in uniaxial tensile testing.

The classical description of flow stress is the Ludwik equation. It gives the strain hardening exponent $n$, valid within range.

For extrapolation of the data to higher strain - as needed for FEM-simulations - several extrapolation methods are used. The (modified) Voce gives best results.

Figure below: Yield curves of EN AW-5754-O (EN AW-AlMg3) according to different regression approaches.

![Yield curves of EN AW-5754-O](slide)

Red line marks begin of extrapolation

Source: VAW
### Table below: Material data and coefficients of yield curve fittings of EN AW-5754-O (EN AW-AlMg3)

<table>
<thead>
<tr>
<th>Testing direction</th>
<th>0</th>
<th>45</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>GPa</td>
<td>70.5</td>
<td></td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td></td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>2.69</td>
<td></td>
</tr>
<tr>
<td>Normal anisotropy</td>
<td>0.64</td>
<td>0.76</td>
<td>0.64</td>
</tr>
<tr>
<td>Proof stress</td>
<td>MPa</td>
<td>97</td>
<td>93</td>
</tr>
</tbody>
</table>

#### Yield curve regression acc. to Ludwik: \( k_1 = k^2q^0 \) and \( k_2 = R_{0.2} \) for \( q < q_{\text{lim}} \)

<table>
<thead>
<tr>
<th>Coefficient ( k ) (MPa)</th>
<th>451.7</th>
<th>452.3</th>
<th>427.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain hardening exponent ( n )</td>
<td>0.2965</td>
<td>0.3000</td>
<td>0.2929</td>
</tr>
</tbody>
</table>

#### Yield curve regression acc. to Hockett-Shenby: \( k_2 = k_0 \sqrt{k_0/k_0 + \exp(m^* q^0)} \)

<table>
<thead>
<tr>
<th>Coefficient ( k_0 ) (MPa)</th>
<th>89.6</th>
<th>85.9</th>
<th>86.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient ( k_2 ) (MPa)</td>
<td>275.7</td>
<td>263.9</td>
<td>264.2</td>
</tr>
<tr>
<td>Coefficient ( m )</td>
<td>12.15</td>
<td>12.09</td>
<td>12.3</td>
</tr>
<tr>
<td>Coefficient ( n )</td>
<td>0.9378</td>
<td>0.9477</td>
<td>0.9472</td>
</tr>
</tbody>
</table>

#### Yield curve regression acc. to Voce: \( k_2 = k_{01} \exp(x_{02} + x_{03} \cdot q^0) \cdot (1 + \exp(x_{04} \cdot q^0)) \)

<table>
<thead>
<tr>
<th>Coefficient ( k_{01} ) (MPa)</th>
<th>91.2</th>
<th>87.0</th>
<th>88.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient ( k_{02} ) (MPa)</td>
<td>140.4</td>
<td>134.4</td>
<td>139.6</td>
</tr>
<tr>
<td>Coefficient ( k_{03} ) (MPa)</td>
<td>193.9</td>
<td>186.0</td>
<td>160.5</td>
</tr>
<tr>
<td>Coefficient ( k_{04} ) (MPa)</td>
<td>282.9</td>
<td>2616</td>
<td>2641</td>
</tr>
</tbody>
</table>

Source: VAW
1.6.4 Forming limit diagram

Forming Limit Diagrams (FLD) are used to evaluate and the result of a forming simulation by displaying the local distance to strain limits.

FLDs show the maximum amount of strain before failure by necking or fracture as a function of the state of 2-dimensional deformation ("major and minor strain").

FLDs are commonly determined by experiments. They can also be calculated using flow curves (FC), yield loci and an instability criterion.

Figure below: Forming limit diagram of EN AW-5754-O (EN AW-AlMg3).

![Forming limit diagram of EN AW-5754-O](source: VAW)

Figure below: Forming limit diagram of AA 6016-T4 (AlSi1.2Mg0.4).

![Forming limit diagram of AA 6016-T4](source: ALCAN (Suisse))
1.6.5 Yield locus

Literature:


The von Mises criterion is the classical description of the yield locus for isotropic materials. For sheets that show some anisotropy a number of extended yield criteria are available, some already implemented in commercial FEM codes:

The Hill 1948 quadratic criterion is generally used for basic studies. In forming simulation, more elaborate material models are used for a better description of the plastic behaviour of the material (e.g. Barlat, Hill 1990, Vegter, etc.). Developments are ongoing, therefore it may be advisable to check which material model is specifically implemented in a commercial FEM code.

Anisotropy of sheet is caused by texture, depends on alloy and processing history and may vary between suppliers.

Figure: Graph showing yield surface of EN AW-5182-O fitted with several yield criteria.
1.6.6 Comparison aluminium / steel

Literature:


- In comparison to steel, aluminium automotive sheet alloys in tensile testing show similar uniform elongations, lower total elongations, higher work hardening coefficients (n-values) and lower Lankford coefficients (r-values).

- High work hardening (n-values) generally implies better overall formability. They may vary with strain (reaching a maximum around 5%). The correlation of sheet formability with tensile test elongation data is limited and poor with r-values.

- Low yield stress is preferable to control springback and for 6xxx outer panel sheet it is beneficial for hem flanging performance.

- In contrast to steel which shows a significant effect of the material thickness on the Forming Limit Diagram (Keeler formula), the influence of the material thickness in aluminium is minor (predominantly a geometrical effect).

![Load-elongation curve for steel and aluminium alloys](image1.png)

Source: Pechiney

Examples of load-elongation (technical stress-strain) curves for some steel and aluminium alloy sheet (tensile tests with identical sample size: 1mm thick, 20mm wide, 80mm gauge length).
1.7 Microstructure and surface

1.7.1 Surface roughening during sheet forming

For outer panels high quality surface finish is required for stamped and painted part. The degree of change of surface topography during forming is influenced by the following factors:

- **Initial roughness** of the sheet surface:
  Smooth surfaces roughen more!

- **Degree of forming**: The increase of surface roughness is approximately proportional to the degree of deformation.

- **Grain structure and size** ("Orange-peel" effect): Coarse grain size (above 40 - 50 µm) or non-uniform texture result in greater roughening!

- **Strain markings**: Strain markings depend on alloy system and thermo-mechanical processing.

"Strain markings" are roughening with stronger directionality and are typical of non-"stretcher-strain-free" AlMgMn alloys (Type A and B lines) as well as "ridging" or "roping" in highly textured AlMgSi alloys, see examples in fig. below.

![Left to right: Strain marking due to "Roping" (6xxx alloys), Type "A" and "B" stretcher strains (5xxx alloys)]

Source: Corus

All these effects result in a corrugated appearance and in unacceptable finish quality of the painted part. Also, severe ridging may decrease formability.
1.7.2 "Roping" on formed AlMgSi sheet

Literature:

The cause of roping is groups of similarly oriented grains aligned in the rolling direction resulting in a series of fine ridges during forming operations. The parallel repetitive nature of the lines leads to their description as "paint brush lines".

The markings are not readily visible at the surface of the formed panel, but if present, will become evident by stoning transverse to the rolling direction. Roping markings appear strongly after electro-coating while successive paint layers may level the effect.
1.7.3 Strain markings on formed AlMgMn sheet

Literature:

5xxx series (Al-Mg-Mn) sheet alloys are prone to develop strain markings due to serrated yielding or strain aging. They are caused by low mobility of dislocations due to solute pinning. Two types of strain markings may develop:
1. Type A: Needle and flame like appearance, caused by serrated yielding (Lüders bands)
2. Type B: Parallel streaks aligned about 58° to the loading direction, caused by dynamic strain ageing (PLC, "Portevin-Le Chatelier effect")
Type A can be avoided and "strecher strain free (ssf)" sheet can be produced by controlling grain size, quenching after annealing at high temperature, light deformation after annealing, or by alloying with Cu and/or Zn.

The stress amplitude of the serrations of type B and the extent of serrated yielding increases with decreasing grain size and increasing Mg content.
1.8 Corrosion resistance

1.8.1 General corrosion resistance ratings of automotive sheet alloys

Literature:


<table>
<thead>
<tr>
<th>Alloy</th>
<th>Temper</th>
<th>Rating</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>AW-1050A</td>
<td>Soft</td>
<td>4</td>
<td>Unaltered aluminium has high corrosion resistance</td>
</tr>
<tr>
<td>AW-3003</td>
<td>Soft</td>
<td>4-5</td>
<td>Various alloys of the 3xxx series have a corrosion resistance ratings of 4 to 5.</td>
</tr>
<tr>
<td>AW-6005</td>
<td>Soft</td>
<td>4-5</td>
<td>Alloys of the 5xxx series have good corrosion resistance, approaching that of the 3xxx and are superior to 6xxx alloys. Addition of Magnesium &gt; 3% may reduce corrosion resistance, if exposed for long periods at temperatures &gt; 80°C.</td>
</tr>
<tr>
<td>AW-5052</td>
<td>Soft</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>AW-1054</td>
<td>Soft</td>
<td>3-4</td>
<td></td>
</tr>
<tr>
<td>AW-5053</td>
<td>Soft</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>AW-5152</td>
<td>Soft</td>
<td>3-4</td>
<td></td>
</tr>
<tr>
<td>AA-6016</td>
<td>T6*)</td>
<td>3</td>
<td>Alloys of the 6xxx series have good to very good corrosion resistance. Copper additions, usually added to increase strength, may have a detrimental affect on corrosion and are therefore limited to small amounts. Alloys with Silicon in excess may show susceptibility to intergranular corrosion.</td>
</tr>
<tr>
<td>AA 6161A</td>
<td>T6*)</td>
<td>3-4</td>
<td></td>
</tr>
<tr>
<td>AA 6002</td>
<td>T6*)</td>
<td>3-4</td>
<td></td>
</tr>
<tr>
<td>AA 6111</td>
<td>T8*)</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

*) or equivalent paint bake temper
1.8.2 Effects of magnesium on corrosion resistance of Al-Mg alloys

Literature:


Al-Mg-Mn alloys show superior corrosion resistance and are therefore used preferentially in marine applications.

However, for Mg contents > 3% intercrystalline corrosion may occur after long time exposure to elevated temperatures (> 60°C).

Effect of Mg-content on strength and intercrystalline corrosion of Al-Mg alloys

Source: Wieser, Miebach, VAW
1.9 Thermal stability

1.9.1 Contents

Properties and behaviour of age-hardened and strain-hardened aluminium alloys can be affected by exposure to temperature effects occurring at ambient temperatures during storage or at elevated temperatures during service.

Storage of naturally aged (T4-temper) material over longer periods may increase the yield strength and spring-back and concurrently reduce formability prior to forming operation. At the same time, the artificial ageing response during paint baking cycles may be impaired.

Strain-hardened non-age-hardening alloys may experience reduction of static strength at paint baking temperatures due to recovery.

The following pages illustrate these temperature effects especially for 6xxx and 5xxx automotive sheet alloys.

Contents:

Thermal stability of 6xxx series alloys (AlMgSi type)
- T4 temper
- Effect of storage time on strength and formability
- Effect of storage time on paint bake response
- Over-ageing of 6xxx series alloys

Thermal stability of non-heat-treatable Al-alloys
- Reduction of work-hardening due to recovery
- Sensibilisation of 5xxx alloys for IC
1.9.2 T4 temper stability of 6xxx series alloys (AlMgSi type)

See also:
- AAM – Materials – 2 Alloy constitution > Heat treatment > Solution treatment and ageing > Special ageing effects in 6xxx alloys: stabilised T4 tempers (T4*)

Literature:

AlMgSi sheet alloys show good formability in the as-delivered condition (T4 temper) and high age-hardening potential after final paint bake cycle (T6 temper) for high in-service strength. But both properties can change during thermal exposure and long time storage. In T6 condition softening due to over-ageing occurs at elevated temperatures; in T4 condition natural ageing occurs during room temperature storage, resulting in:
- T4 yield-strength and springback increases.
- Bending and hemming performance degrades.
- Elongation, n-values, and LDH results are hardly affected.

However, mechanical properties and aging response can be controlled by appropriate heat treatment (T4+), which stabilises strength increase during storage and accelerate age-hardening response during paint baking (see also Links).

Figure: Diagram showing effects of room temperature storage on the T4 yield strength of different Al-Mg-Si alloys.

![Diagram showing effects of room temperature storage on the T4 yield strength of different Al-Mg-Si alloys.](Source: ALCAN (Switzerland))
1.9.3 Effect of storage time on formability of 6xxx alloys

Literature:

Mechanical properties of 6xxx-T4 alloys change gradually from the moment the material is quenched at the rolling plant (natural ageing). Material stored for long periods (several months), may therefore not be representative of production material:
- T4-strength increases with storage time. It has to be ensured that older material is within specified mechanical property limits before using it for forming trials.
- Springback increases slightly due to the yield strength increase.
- Elongation, n-values, and LDH results are hardly affected.
- Bending and hemming performance degrade.

Low temperature storage reduces the effects of natural ageing. Effects are accelerated by increased storage temperature.
1.9.4 Effect of storage time on paint bake response of 6xxx alloys

With progress of natural ageing the yield strength before paint bake cycle increases, whereas the strength after paint bake cycle decreases.

By using special heat treatment techniques (e.g. interrupted quenching, pre-ageing or retrogression) it is possible to stabilise the mechanical properties, i.e. strength increase during storage will be substantially decreased. Furthermore the paint bake response may be strongly accelerated. This special, non-standardised temper is designated as "T4+" in this Manual.

Suppliers should be asked for recommended T4 tempers depending on the requirements of part design and fabrication.

Figure: Effect of storage time at RT on the yield strength of AA6016-T4 before and after the paint bake cycle (180°C/30min).

Source: CORUS
1.9.5 Over-ageing of 6xxx series alloys at elevated temperatures

Literature:
MIL-HDBK-5 E, June 1, 1987

Over-ageing may happen during long term exposure at elevated temperatures. Such conditions may prevail in service for parts in body structure and chassis applications near heat sources (e.g. engine block or exhaust system). Over-ageing decreases the strength of parts, but not their ductility.

Because of the stabilisation effects of artificial ageing or paint curing over-ageing of body sheet components will usually not happen during in-service conditions.

In some cases, slightly over-aged 6xxx alloys may provide better crash resistance.

Figure: Effect of exposure at different temperatures on elevated-temperature yield strength of AA6061-T6.

![Graph showing the effect of exposure at different temperatures on elevated-temperature yield strength of AA6061-T6.](source: VAW)
1.9.6 Thermal stability of non-heated-treatable Al-alloys

See also:
- AAM – Materials – 3 Designation system > Wrought alloys > H-Tempers for strain-hardening wrought alloys (EN 515)
- AAM – Materials – 2 Alloy constitution > Heat treatment > Annealing

For non-heat-treatable Al-Mg-Mn alloys additional strengthening is achieved by work hardening during cold rolling or cold forming (Hxx tempers). Some of it is lost at elevated temperatures due to softening mechanisms like recovery and recrystallization.

Example (s. fig.): Cold rolled sheet of AA5454 (temper H18) shows minor exponential softening by recovery exposed to temperatures below 200°C. Above 200°C recrystallization occurs that leads to fast and significant softening.

![Isothermal softening curves for AA5454-H18](Courtesy of VAW)
1.9.7 Thermal stability of 5xxx series alloys (AlMgMn)

See also:
   - AAM – Materials – 4 Microstructure and properties > Corrosion behaviour > Intergranular corrosion

Alloys with > 3% Mg may be affected in their corrosion resistance by extended exposure at temperatures between 60 and 200°C. Surplus Mg may precipitate as Al8Mg5 at grain boundaries to form a continuous seam which - exposed to a corrosive environment - will be sensitive to intergranular corrosion "IC".

A specific thermal treatment can be applied for stabilisation which can significantly reduce IC susceptibility.

*In any case this must be considered carefully and discussed with the material supplier before applying Al>3%Mg alloys to any IC critical application!*

**Example:**
Microstructure of a stabilized EN AW-5182-O with discontinuous Al8Mg5-precipitates at grain boundaries.

![Microstructure of a stabilized EN AW-5182-O with discontinuous Al8Mg5-precipitates at grain boundaries.](Source: VAW)

**Example:**
Microstructure of EN AW-5182-O with continuous seams of Al8Mg5-precipitates at grain boundaries (high IC susceptibility).

![Microstructure of EN AW-5182-O with continuous seams of Al8Mg5-precipitates at grain boundaries.](Source: VAW)
1.10 Crashworthiness

Aluminium and its low to medium strength alloys perform well under high strain rate deformation, i.e. both flow curve and ductility increase with increasing strain rate.

Aluminium is therefore successfully applied in crash sensitive and safety parts.

Flow curves under high rates of strain are currently being updated for automotive aluminium alloys. Selected data will be presented here when released.

Aluminium HF-welded tubes as energy absorbing elements for bumpers

Source: VAW

Impact behaviour of HF-welded tubes made from rolled 5xxx alloy strip

Source: VAW