Thermal Treatments During Processing of Aluminum Extrusion Alloys

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6xxx Extruded Products
6xxx Extruded Products

Product Requirements

- Strength/Hardness
- Formability
- Surface
  - As-extruded
  - Anodized
- Dimensions
- Low Processing Cost
  - High extrusion speed
  - High recovery

Process Steps

- Ingot Casting
- Homogenization/Cooling
- Reheating
- Extrusion
- Cooling/Quenching
- Stretching
- Aging to Prescribed Temper
6xxx Alloy Metallurgy

- Strengthened by precipitation of Mg$_2$Si
- Higher levels of Mg$_2$Si lead to higher strength
- Fe impurities are limited to improve surface quality (at high extrusion speeds)
- Stronger alloys such as 6061 or 6082 have additions of Cr and/or Mn to control recrystallization
Basic Temper Designations

F  As-Fabricated (no property limits)
O  Annealed (furnace softened)
H  Strain-Hardened
   (Non Heat-Treated products only)
W  Solution Heat-Treated
T  Thermal Treatment
   (Excluding F, O, or H)
Precipitation Hardening Made Simple

\[ \text{Mg}_2\text{Si in Al Alloys - Similar to Sugar in Tea} \]

As energy of tea increases (from temperature or stirring),
more sugar dissolves (goes into solution).

As energy of tea decreases (add ice),
sugar precipitates (comes out solution).
6xxx Extrusion Billet

- Free from inclusions and hydrogen
- Reduced amount of surface segregation
- Uniform as-cast grain structure and distribution of intermetallic phases

MgO Films
6xxx Extrusion Billet

- Free from inclusions and hydrogen
- Reduced amount of surface segregation
- Uniform as-cast grain structure and distribution of intermetallic phases
Billet and Extrusion Thermal Practices

- Homogenization, reheat and extrusion heating should not be separated into distinct thermal processes
- Managing the distribution of the Mg$_2$Si precipitates is the key!
- Best practice involves control and linkage of all thermal practices including deformation heating in the die
Processing Effects on Properties

- Fine Mg$_2$Si is needed after aging to strengthen the final product.
- Precipitation of coarse Mg$_2$Si prior to or during extrusion can decrease the mechanical properties.
- Coarse Precipitation that decreases the strength of the product will occur if the billet or extrusion is held at 230°C (450°F) < T < 500°C (932°F) solvus for any significant length of time.
Homogenization

Objective is to improve microstructure of Cast Billets by:

1. Minimizing the negative effect of Fe - Phase transformation $\beta \rightarrow \alpha$
2. Eliminating or minimizing grain or micro segregation (Homogenizing)
4. Dissolving soluble Mg2Si in order to control precipitation during cooling.
5. Temperature control ($< 570^\circ C(1060^\circ F)$) is required to avoid melting

As-cast: $\beta$ Al-Fe
Microstructure Changes During 6xxx Homogenization

As-Cast Billet

β-Al-Fe Rods

Homogenized 6063 Billet
Homogenization Best Practices

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Temperature</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>6005*</td>
<td>1050-1080 F</td>
<td>min 4 hr</td>
</tr>
<tr>
<td>6060*</td>
<td>1075-1085 F</td>
<td>min 2 hr</td>
</tr>
<tr>
<td>6061</td>
<td>1050-1080 F</td>
<td>4 hr</td>
</tr>
<tr>
<td>6063*</td>
<td>1060-1080 F</td>
<td>min 3 hr</td>
</tr>
<tr>
<td>6082</td>
<td>1035-1060 F</td>
<td>min 16 hr</td>
</tr>
</tbody>
</table>

* forced air cooling, >360F/hr, <120F in 3 hours is required to control the size and amount of Mg₂Si precipitated (*1 hour to <300°C (570°F)*
Billet Reheat

- Best practice reheat occurs with a peak metal temperature below the solvus.
- This requires that the billet be heated quickly and the reheat be paced with the press.
- Induction reheat accommodates heating below the solvus.
- Gas fired furnaces should be operated such that time above 360°C (680°F) is minimized.
- Above 360°C (680°F), Mg$_2$Si precipitates quickly and may not be dissolved during heating in the die, during extrusion.
Precipitate Coarsening During Billet Reheat

- SEM Photomicrograph shows coarse Mg$_2$Si which has precipitated as a consequence of a prolonged delay at the reheat temperature.
Maximizing Extrusion Speed and Surface Quality

Too low to break out

Limit Diagram

Surface is prone to cracking “hot shortness”

Too low to reach Mg2Si dissolution temperature

Extrusion Speed

Insufficient Pressure

Inadequate Surface

Inadequate Properties

Billet Temperature
Speed Tears, Checking

- high temperature / speed
- poor die design
- large Mg$_2$Si precipitates
- poor homogenization
- liquation layer extruded
Process OK!

**Solvus Temperature**

Local Melting Point

- **Exit temp.**

3000 psi

- **Low billet temp./Low speed (Low mech. prop.)**

- **High billet temp./High speed (Tearing/speed cracks)**

Legend:

- Process OK!
Extrusion Temperature Limits for 6xxx Alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Solvus Temp</th>
<th>Melting Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>6060</td>
<td>920 F</td>
<td>1160 F</td>
</tr>
<tr>
<td>6063</td>
<td>960 F</td>
<td>1160 F</td>
</tr>
<tr>
<td>6005</td>
<td>960 F</td>
<td>1125 F</td>
</tr>
<tr>
<td>6061</td>
<td>1040 F</td>
<td>1123 F</td>
</tr>
<tr>
<td>6082</td>
<td>1060 F*</td>
<td>1103*</td>
</tr>
</tbody>
</table>

* Calculated

Solvus temperatures for these alloys are calculated based on mid-range compositions for these alloys. Since extrusion alloys are typically lean in composition, solvus values are somewhat higher and melting temperatures are lower compared to typical plant practice.
Quench rate required to maintain properties depends on alloy content.

Stronger alloys require higher cooling rates. Alloy, speed, equipment, and section size will dictate type of cooling required.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Minimum Cooling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>6060</td>
<td>2 - 3.5°F/s</td>
</tr>
<tr>
<td>6063</td>
<td>&gt; 2.5°F/s</td>
</tr>
<tr>
<td>6005</td>
<td>2.5 - 4.5°F/s</td>
</tr>
<tr>
<td>6082</td>
<td>&gt; 7°F/s</td>
</tr>
<tr>
<td>6061</td>
<td>&gt; 7°F/s</td>
</tr>
</tbody>
</table>

Values for 6082 and 6061 are considered bare minimum. Typically faster cooling rates are desired to develop sufficient strength.
# Pros and Cons for Different Quench Methodologies

<table>
<thead>
<tr>
<th>Quench Type</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air, Fans</td>
<td>Cheap, clean</td>
<td>Slow, dead spots possible, limited quench rate</td>
</tr>
<tr>
<td>Air Amplifiers</td>
<td>Cheap purchase, can “mistify”, good for fill in</td>
<td>Consumes compressed air</td>
</tr>
<tr>
<td>Air, Ducted Blowers</td>
<td>Good rate (for air), no distortion</td>
<td>Capital intensive, and expensive to run (HP)</td>
</tr>
<tr>
<td>Mist</td>
<td>Faster quench rate, minimal distortion</td>
<td>Mist containment</td>
</tr>
<tr>
<td>Spray</td>
<td>Cheap to run, variable quench rate</td>
<td>Initial cost, containment, distortion, may require cooling loop</td>
</tr>
<tr>
<td>Standing Wave</td>
<td>Immersion quench rate, inexpensive to run</td>
<td>Distortion, may require cooling loop, fixed quench condition</td>
</tr>
</tbody>
</table>
“Quench Sensitivity”

Loss in a given property with a slower quench

Quenching must be fast enough to retain Mg and Si in solution. Alloy 6063 example

Quench Sensitivity for 6xxx Alloys
Quench Sensitivity of Other Properties

- Other properties such as “toughness” or crash resistance can be affected by quench rate.
- Precipitation of Mg$_2$Si can sensitize grain boundaries to fracture.
- So structural products may require higher cooling rates than expected only on the basis of strength.
Critical Cooling Rate for 6XXX Alloys

![Diagram showing critical cooling rate for 6XXX alloys. The diagram includes a quench sensitivity rate (40 K min⁻¹) for 6063 alloy, a 6063 extrusion shape cooling curve for full strength, and various temperature ranges for precipitation and rejection.]
Precipitation During Aging

Solid Solution  \xrightarrow{\text{Soft}} \xrightarrow{\text{Strength Increases}} \xrightarrow{\text{Peak Strength}} \xrightarrow{\text{Overaged}}

Coherent Precipitates

- $\beta''$ (zones)
- $\beta'$ (rods)

Partially Coherent Precipitates

Incoherent Precipitates

- $\beta$ (Mg$_2$Si plates)

$\bigcirc$ Aluminum atoms; $\bullet$ Foreign atoms (e.g. Cu)
Temperature Effects on Natural Aging

- Lower temperatures will slow down natural aging.
- Plant ambient conditions can affect the development of T4 tempers.
Natural Aging of 6xxx Extrusions

6005 – .45 Mg  - .80 Si
6061 – .86 Mg  - .80 Si
6351 – .51 Mg  - .91 Si
6063 – .51 Mg  - .47 Si
CH36 – .46 Mg  - .42 Si
CD27 – .48 Mg  - .32 Si

Note difference due to Excess Si: 6005 vs 6063
Artificial Aging Curves for 6061 Alloy
Aging of 6xxx Extruded Products

- Balance desired properties and cycle time
- Understand furnace variability
Tempers for 6xxx Extruded Products

- **T1** – Cooled from elevated temperature and naturally aged at room temperature to a substantially stable condition.
  - AA property limits: 9 ksi (yield), 17 ksi (tensile)
- **T4** – Quenched from elevated temperature heat treatment and naturally aged at room temperature to a substantially stable condition.
  - AA property limits: 10 ksi (yield), 19 ksi (tensile)
- **T52** – Cooled from elevated temperature working operation and artificially aged
  - AA property limits: 16-25 ksi (yield) and 22-30 ksi (tensile)
- **T6** – Cooled or quenched from elevated temperature and artificially aged to a near peak strength condition
  - Can be designated 6063-T6 regardless of solution HT method as long as 25 ksi (yield) and 30 ksi (tensile) minimums are met
Additional Digits for Thermally Treated Tempers

- **Tx51**: Stress-relieved by stretching
- **Tx52**: Stress-relieved by compression
- **Tx54**: For die forgings stress-relieved re-striking cold in the finish die
- **Tx510**: For extruded bar, rod and tube and drawn tube, no further straightening
- **Tx511**: For extruded bar, rod and tube and drawn tube, may be straightened
The effect of floor aging time on T6 strength depends on alloy:

- High solute alloys show loss of T6 strength
- Low solute alloys show gain in T6 strength

Formability little affected by NA interval
## Summary: Influence Matrix

<table>
<thead>
<tr>
<th></th>
<th>Strength</th>
<th>Surface</th>
<th>Dimensions</th>
<th>Extrusion Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy Comp.</td>
<td>High</td>
<td>High</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Billet</td>
<td></td>
<td>High</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Homo</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Cooling</td>
<td>High</td>
<td></td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Reheat</td>
<td>High</td>
<td></td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Extrusion</td>
<td></td>
<td>High</td>
<td>High (Dies)</td>
<td>High</td>
</tr>
<tr>
<td>Quench</td>
<td>Medium</td>
<td></td>
<td>High (Distortion)</td>
<td></td>
</tr>
<tr>
<td>Stretch</td>
<td></td>
<td></td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>