Metallurgy of Aluminum Die Casting Alloys

EC 305
Dave Neff
OUTLINE

• Where aluminum comes from
• Why alloys are useful
• Alloy designation and nomenclature
• Specific roles of alloy elements
• Properties of aluminum and alloys
• Impurities in aluminum melting
• Melt Treatment
• Quality Analysis
• Alternative Casting Processes
Why Aluminum?

- Relatively abundant
- Amenable to multiple casting processes
- Desirable physical and mechanical properties:
  - Conductivity, cosmetics, thermal stability, non-magnetic, machinable
  - Strength improvement through heat treatment
Melting Furnace -> Transfer Ladle -> Rotor Degas or Flux Injection

Mold -> Casting Spoon or Robot -> Holding or Casting Furnace
“FCC”

An Atom at Each Corner of the Cube and at the Center of Each Face

The structure of *Aluminum*; also of copper, gold, silver

Characteristically, the softer and more ductile metals
“FCC” Visualized
Key Alloying Elements

- major/minor alloy elements
  - Si
  - Fe
  - Cu & Mg
    - Zn
    - Ni
    - Sn

- microstructure modifiers
  - Mn & Cr
  - Ti & B
  - Na, Sr, Sb & Ca
    - P
Aluminum Association
Casting Alloy Designation System

✓ 1xx = 99.0% minimum purity Al
✓ 2xx = AlCu
✓ 3xx = AlSiCu, AlSiMg, & AlSiCuMg
✓ 4xx = AlSi
✓ 5xx = AlMg
✓ 7xx = AlZn
✓ 8xx = AlSn
The 380 alloy ‘family’ comprises nearly 80% of all HPDC Alloys
## Nominal 380 alloy Composition

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mg</th>
<th>Zn</th>
<th>Mn</th>
<th>Ni</th>
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</thead>
<tbody>
<tr>
<td>Min</td>
<td>7.5</td>
<td>1.3</td>
<td>3.0</td>
<td>0.1</td>
<td>3.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Max</td>
<td>9.5</td>
<td></td>
<td>4.0</td>
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</tbody>
</table>

Sn 0.35, Other 0.5
## Cast Aluminum Alloy Families

### Key Alloy Characteristics

<table>
<thead>
<tr>
<th>ALLOY</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>good die filling</td>
</tr>
<tr>
<td>383</td>
<td>better die fill than 380</td>
</tr>
<tr>
<td>360</td>
<td>corrosion resistance</td>
</tr>
<tr>
<td>384</td>
<td>pressure tightness</td>
</tr>
<tr>
<td>390</td>
<td>wear resistance</td>
</tr>
<tr>
<td>413</td>
<td>fluidity, thin wall capability</td>
</tr>
<tr>
<td>443</td>
<td>corrosion resistance, ductility</td>
</tr>
<tr>
<td>518</td>
<td>machinability, ductility, corrosion resistance</td>
</tr>
</tbody>
</table>
## Physical Properties of Typical Die Cast Alloys

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th>Solidification Range</th>
<th>Electrical Conductivity</th>
<th>Thermal Conductivity</th>
<th>Coefficient of Thermal Expansion</th>
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</thead>
<tbody>
<tr>
<td>A360.1</td>
<td>0.095</td>
<td>1105 - 1035</td>
<td>37</td>
<td>0.27</td>
<td>11.6</td>
</tr>
<tr>
<td>A380.1</td>
<td>0.099</td>
<td>1100 - 1000</td>
<td>27</td>
<td>0.25</td>
<td>11.7</td>
</tr>
<tr>
<td>B380.1</td>
<td>0.102</td>
<td>1100 - 1000</td>
<td>25</td>
<td>0.24</td>
<td>11.7</td>
</tr>
<tr>
<td>383.1</td>
<td>0.099</td>
<td>1080 - 960</td>
<td>27</td>
<td>0.24</td>
<td>11.8</td>
</tr>
<tr>
<td>384.1</td>
<td>0.098</td>
<td>1080 - 960</td>
<td>23</td>
<td>0.23</td>
<td>11.3</td>
</tr>
<tr>
<td>B390.1</td>
<td>0.099</td>
<td>1200 - 945</td>
<td>25</td>
<td>0.32</td>
<td>10.3</td>
</tr>
<tr>
<td>A413.1</td>
<td>0.096</td>
<td>1085 - 1065</td>
<td>39</td>
<td>0.37</td>
<td>11.5</td>
</tr>
<tr>
<td>C443.1</td>
<td>0.097</td>
<td>1170 - 1065</td>
<td>37</td>
<td>0.35</td>
<td>12.3</td>
</tr>
<tr>
<td>518.2</td>
<td>0.094</td>
<td>1150 - 995</td>
<td>24</td>
<td>0.24</td>
<td>13.4</td>
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</tbody>
</table>
## Typical HPDC Alloy Compositions

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td>9 - 10</td>
<td>1.3</td>
<td>0.6</td>
<td>.4 - .6</td>
<td>0.35</td>
</tr>
<tr>
<td>364</td>
<td>7.5 - 9.5</td>
<td>1.5</td>
<td>0.2</td>
<td>.2 - .4</td>
<td>0.1</td>
</tr>
<tr>
<td>380</td>
<td>7.5 - 9.5</td>
<td>2</td>
<td>3 - 4</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>A380</td>
<td>9 - 10</td>
<td>1.3</td>
<td>3 - 4</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>383</td>
<td>9.5 - 11.5</td>
<td>1.3</td>
<td>2 - 3</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>384</td>
<td>10.5 - 12</td>
<td>1.3</td>
<td>3 - 4.5</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>390</td>
<td>16 - 18</td>
<td>1.3</td>
<td>4 - 5</td>
<td>.45 - .65</td>
<td>0.1</td>
</tr>
<tr>
<td>A390</td>
<td>16 - 18</td>
<td>0.5</td>
<td>4 - 5</td>
<td>.45 - .65</td>
<td>0.1</td>
</tr>
<tr>
<td>B390</td>
<td>16 - 18</td>
<td>1.3</td>
<td>4 - 5</td>
<td>.45 - .65</td>
<td>0.5</td>
</tr>
<tr>
<td>413</td>
<td>11 - 13</td>
<td>2</td>
<td>1</td>
<td>0.1</td>
<td>0.35</td>
</tr>
<tr>
<td>518</td>
<td>0.35</td>
<td>1.8</td>
<td>0.25</td>
<td>7.5 - 8.5</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Alloy Source Designation

- **380.0** Casting
- **380.1** Secondary metal source
- **356.2** Primary smelter alloy with tighter composition limits
  - A, B, C, D slight variants on compositions or process-specific
Cooling Curves for Pure Metals

- Zn: 420°C (787°F)
- Al: 655°C (1220°F)
- Cu: 1082°C (1981°F)
- Si: 1430°C (2606°F)
Al-Si Phase Diagram

ALUMINUM-SILICON
BINARY (EQUILIBRIUM) PHASE DIAGRAM

°C  900  800  700  600  500  400  300  20  15  10  5  Al

Si  400  500  600  700  800  900  1000  1100  1200  1300  1400  1500  1600  °F

Liquid

Si + Liquid

Al Solid Solution

Al + Si

577°C (1071°F)

1.65%
Al-Si Phase Diagram

- **Liq.**
- **Liq. + Al**
- **Al**
- **Al + Si**
- **Liq. + Si**

Temperature (°C) vs. wt.% Si

- 700°C
- 600°C
- 500°C
Die Casting Alloy 380
## Aluminum Die Cast Alloys Solidification Range

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Liquidus (F)</th>
<th>Solidus (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td>1105</td>
<td>1035</td>
</tr>
<tr>
<td>413</td>
<td>1085</td>
<td>1065</td>
</tr>
<tr>
<td>443</td>
<td>1170</td>
<td>1065</td>
</tr>
<tr>
<td>380</td>
<td>1100</td>
<td>1000</td>
</tr>
<tr>
<td>390</td>
<td>1200</td>
<td>945</td>
</tr>
<tr>
<td>518</td>
<td>1150</td>
<td>1005</td>
</tr>
</tbody>
</table>
413 Alloy, example of High % Isothermal Solidification

Temperature (°C)

Fraction Solid (%)
413 Alloy, example of High % Isothermal Solidification; Solidification Pattern in Die Casting
518 Alloy, example of **No Isothermal Solidification**; Solidification Pattern in Die Casting

- Dense Skin
- Heaviest Porosity Concentration
Silicon (Si)

• The single most important element
  – fluidity (heat of fusion)
  – castability (high % isothermal solidification)
• Strengthens (combined with Mg and/or Cu)
• Reduces shrinkage
• Increasing silicon reduces thermal expansion
• Increases wear resistance
• Reduces machinability
Latent Heat of Fusion

<table>
<thead>
<tr>
<th>Metal</th>
<th>Latent Heat (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (Al)</td>
<td>~ 395</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>~ 1810</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>~ 275</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>~ 210</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>~ 370</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>~ 100</td>
</tr>
</tbody>
</table>
Silicon Effect on “Fluidity”

- Fluidity (AFS Spiral Length – Inches)
- % Silicon in Alloy
- 1400 °F
- 1300 °F

0 5 10 15 20 25
0 10 20 30 40 50
Copper as an Aluminum Alloying Agent

- Provides solid solution strengthening
- Improves machinability
- Creates age hardening effect through Al-Cu precipitate
- Reduces corrosion resistance
- Alloys with low silicon have poor hot tearing resistance
Magnesium

- Increases strength and hardness
- Improves machinability
- Reduces impact strength and ductility
- In Al-Mag (5xx alloys): poor castability
Zinc

• An acceptable impurity
• Reduces cost
• Increases density but subject to hot shortness and heavy metal segregation
Iron

- A “necessary” impurity
- Reduces soldering tendency
- Improves mechanical properties in small percentages
- Size and shape governs the amount that can be tolerated
- Manganese has a favorable effect on the iron influence
Nickel

Increases elevated temperature strength and hardness
Minor Elements

- Low melting point constituents -- Tin, Lead, Bismuth
  - Hot Shortness
- Refractory metals -- Chromium, Zirconium, Molybdenum, Vanadium
  - High melting point, low solubility
  - Sludge, hardspots
Other Elements

- Strontium, Sodium, Calcium, Antimony – “silicon modifiers”
- Beryllium -- oxide skin former
- Phosphorus – modifier in 390
- Titanium, Boron -- grain refiners
Al-Mg Casting Alloys

• The aluminum-magnesium alloy systems offer excellent mechanical and physical properties (515, 518)
• Machinability, surface finish capability, and corrosion resistance are high.
• Castability is difficult with poor fluidity, drossing, high solidification shrinkage (low Si); unlike 3xx alloys
Hyper-Eutectic 390 Alloy
Hyper-Eutectic 390 Alloy

Principle Characteristics

• Higher Cu, Mg, Si Alloy Content
  – greater hardness, higher elevated temperature properties
  – reduced thermal expansion, greater wear resistance

• Greater heat content to be released
  – greater cooling required
  – longer solidification range
  – tendency for hot shortness and microshrinkage
Hyper-Eutectic 390 Alloy

Principle Characteristics

• Phosphorus refinement not usually required for diecasting

• Sludging
  – less tendency with necessary higher holding temperatures required
  – primary silicon phase is predominant
390 Alloy

P-Refined

Unrefined
Hyper-Eutectic 390 Alloy

Microstructure of hypereutectic 390 alloy

- primary silicon appears as evenly dispersed, block-like, medium grey deposits
Hyper-Eutectic 390 Alloy

Wear Resistance Capability
Skin Effects - PFZ and PSDZ

• Skin layer is common to virtually all aluminum alloy diecastings as a result of fast solidification rate

• In hypoeutectic alloys, smaller volume fraction of primary $\alpha$ phase

• PFZ responsible for pressure tightness
Skin Effects - PFZ and PSDZ

- PSDZ in *hypereutectic* alloys refers to smaller volume fraction of primary *silicon* (beta) phase
- PFZ and PSDZ vary with casting location and diecasting operating variables