Directionally Solidified Aluminum – 7 wt% Silicon Alloys: Comparison of Earth and International Space Station Processed Samples

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This Investigation is a Collaborative Effort with the European Space Agency (ESA) Program:

*Microstructure Formation in Castings of Technical Alloys under Diffusive and Magnetically Controlled Convective Conditions (MICAST)*

The MICAST Microgravity Research Program Focuses on:
- A systematic analysis of the effect of convection on the microstructural evolution in cast Al-alloys.
- Experiments that are carried out under well defined processing conditions.
- Sample analysis using advanced diagnostics and theoretical modeling.

→ The MICAST team investigates binary, ternary and commercial alloys based on the Al-Si system.
Intent

Conduct a Thorough Ground-based Investigation

- Utilize Aluminum – 7wt. % Silicon Alloys
  - Directionally Solidify Samples having an Initial Aligned Dendritic Array
  - Evaluate the Dendritic Microstructure (λ₁, λ₂, λ₃, d) as a function of the Steady-State Processing Conditions (V, G, C₀)

Use the Above for Comparison to Limited # of DS μg Samples

- Partially melt and Directionally Re-Solidify terrestrially grown dendritic mono-crystals of Al-7 wt% Si (9-mm dia, 25 cm long) in microgravity.
Outline

• Microstructural Considerations
• Expectations
• Ground-based Results
• Microgravity Results
• Comparative Comments
Microstructural Considerations

Why Directional Solidification?

Bar chart showing the changes in temperature capability of cast turbine blade alloys as a function of time. The first three alloys in the series are equiaxed, conventional cast. The next one is a monocrystal alloy. The next is a directionally solidified alloy with comparable performance at lower cost. The last two are monocrystal alloys.

Microstructural Considerations: Evaluation

- $\lambda_1$, Primary Dendrite Arm Spacing
- $\lambda_3$, Tertiary Dendrite Arm Spacing
- $d$, Primary Dendrite Trunk Diameter
- Relative Dendrite Grain Orientation

Statistically Compile and Relate to Solidification Processing Conditions of:
- Growth Velocity ($V$)
- Temperature Gradient ($G$)
- Alloy Composition ($C_0$)
Expectations
Solidification Processing in a Microgravity Environment

Advantages:
- Minimize Thermo-Solutal Convection
- Minimize Buoyancy Effects

Intent:
- Produce Segregation Free Samples Grown Strictly by Heat Transfer and Solute Diffusion

Purpose:
- Better Understand the Relationship between Processing – Microstructural Development

Application:
- Maximize Material Properties
Microgravity Processing

Al-7 wt.% Si

Sample Cartridge

ESA Low Gradient Furnace (LGF) Insert

Microgravity Science Research Facility (MSRF) Aboard the ISS
Microgravity Processed Sample MICAST 7

X-ray radiograph of MICAST7

No terrestrial samples which are processed in LGF or SQF equivalent hardware under R and $G_L$ conditions which are identical to MICAST6, MICAST7
Microstructural Comparison: Earth and Microgravity

Al – 7 wt. % Si

Terrestrial:
G = 15 K cm\(^{-1}\)

V = 5 \(\mu\)m s\(^{-1}\)

MICAST6 Seed:
V = 41 K cm\(^{-1}\),
G = 22 \(\mu\)m s\(^{-1}\)

MICAST6:
G = 22 K cm\(^{-1}\)

V = 50 \(\mu\)m s\(^{-1}\)
Microstructural Analysis of Directionally Solidified Al -7 wt. % Si Alloy Samples

1) Primary Dendrite Arm Spacing

2) Primary Dendrite Trunk Diameter

Terrestrial: $G_L = 41$ Kcm$^{-1}$, $V = 85$ mm s$^{-1}$
Primary Dendrite Arm Spacing ($\lambda_1$)
Which primary dendrite arm spacing ($\lambda_1$) to use?

1) Geometrical Spacing: $\sqrt{A/(N - 1)} = 623 \, \mu m$
2) Minimum Spanning Tree:
   Spacing = $412 \pm 138 \, \mu m$
3) Nearest neighbor spacing = $368 \pm 126 \, \mu m$

$\rightarrow$ Theoretical models predict nearest neighbor spacing
Theoretical Models for Primary Dendrite Arm Spacing

\[
\frac{(m_l G_c t - G_t)}{(4\pi^2 \Gamma T_m / r_t^2)} = 1 \text{ for small } R \frac{r_t}{2D_l}
\]

\[
\frac{r_t}{2D_l} = -\frac{G_L \lambda_1^2}{4\sqrt{2}[m_L C_t (1 - k) + \frac{D_L G_L}{R}]}
\]

**Tip radius:**
- **Analytical:** Trivedi (1980)
- **Numerical:** Hunt-Lu (1996)

**Primary spacing:**
- **Analytical:** Trivedi (1984)
- **Numerical:** Hunt-Lu (1996)

**Trunk diameter:** None

**Physical Properties for Al - 7 wt% Si**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_l)</td>
<td>-6.31 K/wt% Si</td>
<td>Metals Handbook, vol. 8 (1973)</td>
</tr>
<tr>
<td>(k)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>(\Gamma)</td>
<td>0.196 (\mu)m K</td>
<td>Gunduz and Hunt (1985)</td>
</tr>
<tr>
<td>(D_l)</td>
<td>(4.3 \times 10^{-9}) m(^2)/s</td>
<td>(Poirier compilation)</td>
</tr>
</tbody>
</table>
Primary Dendrite Trunk Diameter ($\phi$)

Dendrite Tip Radius
Dynamic Growth
Initial Trunk Diameter, $\phi_0$

Stagnant Growth

Final Trunk Diameter, $\phi$

Trunk Diameter Rapidly Increases Until Diffusion Fields Overlap (▼

Reproducible and Predictable Microstructural Constituent

American Society for Gravitational and Space Research (ASGSR), New Orleans, LA
28 Nov 2012 – 2 Dec 2012
Primary Dendrite Trunk Diameter ($\phi$)

"Initial" Trunk Diameter ($\phi_0$) Determination

Primary Dendrite Tip Radius

$$R_{tip}^2 = \frac{4 \pi^2 D I}{\Delta T_0 k V}$$

Fundamental of Solidification, Kurz and Fisher, Trans Tech, 1992


$$\phi_0 = 6.59 \pm 1.3 \ R_{tip}$$
Primary dendrite trunk diameter ($\phi$) model

After $\phi_0$ the trunk diameter increases via dissolution of secondary arms and re-deposition on the trunk until the eutectic reaction.

Assumptions:
2. Secondary arm melts back because of its curvature.
3. Mass of the melted arm deposits on trunk surface where there is negative curvature.

\[
\frac{dl}{dt} = \frac{4 D_l \Gamma}{m_l C_l (1 - k)r^2}
\]  
(1)

\[
\pi \phi h \frac{d\phi}{2 \, dt} = 4 \left( \pi r^2 \frac{dl}{dt} \right)
\]  
(2)

\[
C_l = C_o + R G_m \frac{t}{m_l}
\]  
(3)

\[
\phi^2 \frac{d\phi}{dt} = 32 \frac{D_l \Gamma}{m_l (1 - k) \left( C_o + \frac{R G_m t}{m_l} \right)}
\]  
(4)
Primary dendrite trunk diameter (\( \phi \)) model

\[
\phi^3 = 96 \frac{D_l \Gamma}{R \ G \ (1 - k)} \ln \left\{ \frac{1 + \frac{R \ G \ t}{m_l \ C_o}}{1 + \frac{R \ G \ t_o}{m_l \ C_o}} \right\} + \phi_0^3
\]

Mushy Zone Freezing Time \( \sim \) \( m_l(C_e - C_o)/R G_m \)
Primary Dendrite Arm Spacing ($\lambda_1$)
Primary Dendrite Trunk Diameter ($\phi$)

Comparison of Earth and ISS Processed Samples with Theoretical Models
Primary dendrite arm spacings as compared to Hunt-Lu calculations

ISS-DS: Good agreement with predictions from Hunt-Lu model.
Terrestrial DS ("Not Steepled"): Good agreement with predictions from Hunt-Lu model.
Terrestrial DS ("Steepled"): Convection decreases primary dendrite arm spacing.
Primary dendrite trunk diameter as compared to trunk diameter model calculations, using $r_t$ (Hunt-Lu)

- **ISS-DS**: Good agreement with predictions from the trunk-diameter model.
- **Terrestrial DS ("Not Steepled")**: Good agreement with predictions from model.
- **Terrestrial DS ("Steepled")**: Convection increases trunk diameter.
Conclusions

• Primary dendrite arm spacings of Al-7 wt% Si alloy directionally solidified in low gravity environment of space (MICAST-6 and MICAST-7: Thermal gradient ~ 19 to 26 K cm\(^{-1}\), Growth speeds varying from 5 to 50 \(\mu\)m s\(^{-1}\)) show good agreement with the Hunt-Lu model.

• Primary dendrite trunk diameters of the ISS processed samples show a good fit with a simple analytical model based on Kirkwood’s approach, proposed here.

• Natural convection,
  – decreases primary dendrite arm spacing.
  – appears to increase primary dendrite trunk diameter.

• Need more samples processed in Microgravity
Acknowledgments

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