Morphology of Primary-Dendrite Array: Observations from Ground-based and Space Station Processed Samples

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This Investigation is a Collaborative Effort with the European Space Agency (ESA) Program MICAST (Microstructure Formation in Castings of Technical Alloys under Diffusive and Magnetically Controlled Convective Conditions)

MICAST Purpose: A systematic analysis of the effect of convection on the microstructural evolution in cast binary, ternary and commercial Al-Si based alloys.

This research (MICAST6 and MICAST 7): DS dendritic mono-crystals of Al-7% Si (9-mm dia, 25 cm long) in μg.

Advantages: Minimize Thermo-Solutal Convection
Intent: Produce Segregation Free Samples Grown Under Diffusion-Controlled Conditions
Purpose: Better Understand the Relationship between Processing and Microstructure-Development
Dendritic array morphology depends upon DS processing parameters: $G_l$, $R$, $C_o$, Convection

1. Primary dendrite arm spacing ($\lambda$): Extensive literature (SCN/Metals)
2. Secondary/tertiary arm spacing: Extensive-SCN/Metals
3. Dendrite tip radius: SCN/limited (Al-Cu, Pb-Au, Pb-Pd)
4. Primary dendrite trunk diameter ($\Phi$): Limited (Esaka:Thesis-86, Grugel: 92/95)
Microgravity Processing: Partially remelt and then DS from terrestrially grown dendritic mono-crystal in μg.
Microgravity Processed Sample MICAST 7

Eutectic Melt Back / Isotherm

X-ray radiograph of MICAST7

MICAST7
Directionally solidified Al-7 wt% Si alloy

Reaction
No reaction

Alumina-1

Eutectic Melt Back

Alumina crucible
Terrestrial processing
Graphite crucible (~9 mm ID, ~19 mm OD), 10^-4 torr vacuum

Don’t have terrestrial samples which are processed in LGF or LGFQ equivalent hardware under R and G_l conditions which are identical to MICAST6, MICAST7
MICAST6: ESA-Low Gradient Furnace (1-hr heat-up, 5-hr hold, $G_l \approx 20$ K cm$^{-1}$): 3.8 cm at 5 $\mu$m s$^{-1}$, 11.3 cm at 50 $\mu$m s$^{-1}$

Temperature gradients at nominal liquidus and solidus isotherms
(note: only solidification portion is shown)
MICAST6: ESA-Low Gradient Furnace (1-hr heat-up, 5-hr hold, $G_i \sim 20$ K cm$^{-1}$): $3.8$ cm at $5$ μm s$^{-1}$, $11.3$ cm at $50$ μm s$^{-1}$

 Isotherm velocity vs. position along the Al-Si rod

(note: both melting and solidification are shown)

Data not available due to thermocouple placement. Rod length is 245 mm.
Comparison of microstructures: Al-7% Si directionally solidified on ground and on ISS (MICAST6)

MICAST6 SEED
41 K cm\(^{-1}\), 22 \(\mu\)m s\(^{-1}\)

MICAST6: 20 K cm\(^{-1}\)

Convection causes dendrite clustering (steepleing) at low thermal gradient and growth speeds during terrestrial DS.
Typical analysis of directionally solidified Al-7 wt% Si alloy samples (Terrestrial: $G_l=41 \text{ Kcm}^{-1}$, $R=85 \mu\text{m s}^{-1}$, $G_m=51\text{K cm}^{-1}$)

Primary dendrite trunk diameter

Primary dendrite arm spacing???
Which primary dendrite arm spacing to use?

Primary spacing ($\sqrt{A/(N−1)}$) = 623 µm
Nearest neighbor spacing = 368±126 µm

Primary spacing by $\sqrt{A/(N−1)}$ method is 1.69 times the nearest neighbor spacing ➔ Theoretical models predict nearest neighbor spacing
Theoretical models for primary dendrite arm spacing

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

\[
r_t = -\frac{G_L \cdot \chi_1^2}{4\sqrt{2}[m_L \cdot C_t (1-k) + \frac{D_L G_L}{R}]}
\]

<table>
<thead>
<tr>
<th></th>
<th>Analytical</th>
<th>Numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk diameter:</td>
<td>None</td>
<td></td>
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</table>

Physical Properties for Al- 7 wt% Si

<table>
<thead>
<tr>
<th>Co</th>
<th>7 wt% Si</th>
<th></th>
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<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}) m²/s</td>
<td>(Poirier compilation)</td>
</tr>
</tbody>
</table>
Primary dendrite trunk diameter ($\phi$)

Esaka Thesis (1986): Trunk diameter increases rapidly near the tip till $\sim 10$ side-branch formations. He measured this initial trunk diameter ($\phi_0$). Eighty DS experiments (four SCN-Acetone alloys grown with various R and G_i)

$D_i G_i k/(m_i R C_o (k-1))$]: More branched dendritic morphologies will be located towards the left, and less-branched/cellular towards the right side of the X-axis.

$(\text{Initial trunk diameter } (\phi_0)/\text{tip radius}) = 6.59\pm1.3$
Primary dendrite trunk diameter ($\phi$) model

1. The trunk diameter ($\phi$) increases rapidly near the tip till time, $t_o = 22*\frac{r_t}{R}$), when $\phi = \phi_o = 6.59 \ r_t$ (paraboloidal envelope near tip).
Primary dendrite trunk diameter ($\phi$) model

2. After $t_o$ the trunk diameter increases via remelting of 4-side arms ($r$) and deposition of melted arm material on “trunk surface “over length $h” = \phi$.

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.

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

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

\[
C_l = C_o + R G_m t/m_l \quad (3)
\]

\[
\phi^2 \frac{d\phi}{dt} = 32 \frac{D_l \Gamma}{m_l (1-k)(C_o + R G m t/m_l)} \quad (4)
\]
Primary dendrite trunk diameter (ρ) model

\[
\phi^3 = 96 \frac{D_l \Gamma}{R G m (1 - k)} \ln \left\{ \frac{1 + \frac{R G m t}{m_l C_o}}{1 + \frac{R G m t_o}{m_l C_o}} \right\} + \Phi_0^3
\]

Mushy zone freezing time \( \sim m_l(C_E - C_o)/R G m \)

Use tip radius \( r_t \) predicted from Trivedi (1980) or Hunt-Lu (1996) models to get the initial trunk diameter \( \phi_0 = 6.59 r_t \) in order to predict the processing parameter dependence of “Primary dendrite trunk diameter” from above relationship.
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 μm s\(^{-1}\)) show a good agreement with predictions from Hunt-Lu and Trivedi models.

• 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.
Acknowledgements

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