Growth speed and thermal gradient dependence of primary dendrite trunk diameter in directionally solidified Al-Si alloys

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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)
Typical analysis of directionally solidified Al-7 wt% Si alloy samples (Terrestrial: $G_L=41\text{ Kcm}^{-1}$, $R=85\text{ \mu m s}^{-1}$, $G_m=51\text{ K cm}^{-1}$)

Primary dendrite trunk diameter

Primary dendrite arm spacing
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 Gi)

\[
D_l G_l k/(m_l R C_o (k-1)) \quad \text{: More branched dendritic morphologies will be located towards the left, and less-branched/cellular towards the right side of the X-axis.}
\]

(Initial trunk diameter (\(\phi_0\))/tip radius) = 6.59±1.3
1. The trunk diameter ($\phi$) increases rapidly near the tip till time, $t_o = 22*r_t/R$, when $\phi = \phi_o = 6.59 \times r_t$ (paraboloidal envelope near tip).
Primary dendrite trunk diameter ($\phi$) model

2. After $t_0$ 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.

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

\[ \pi \phi h \frac{d\phi}{2 dt} = 4 \pi r^2 \frac{dl}{dt} \]  \hspace{1cm} (2)

\[ C_l = C_o + R G_m t/m_l \]  \hspace{1cm} (3)

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

$$
\phi^3 = 96 \frac{D_l \Gamma}{RGm (1 - k)} \ln \left\{ \frac{1 + \frac{RGm t}{m_lC_o}}{1 + \frac{RGm t_o}{m_lC_o}} \right\} + \Phi_o^3 \tag{5}
$$

Mushy zone freezing time $\sim m_l(C_E - C_o)/RG_m$

Use tip radius ($r_t$) predicted from Trivedi (1980) or Hunt-Lu (1996) models to get the initial trunk diameter $\phi_o = 6.59 \ r_t$ in order to predict the processing parameter dependence of “Primary dendrite trunk diameter” from above relationship.
Primary dendrite trunk diameter

Lines are predictions from Eq: 5 using $r_t$ (Trivedi) 
($G_l=150$ K cm$^{-1}$, $G_{mush}$ (listed in brackets))

Equation 4 has a reasonable fit with experimentally observed solute content and growth speed dependence (whether we use $r_t$ predictions from Trivedi or Hunt-Lu).
Primary dendrite trunk diameter (Al-6wt% Si)

\(G_l=150 \text{ and } 50 \text{ K cm}^{-1}\)

Lines are predictions from Eq: 5 using \(r_t\) (Trivedi)

Equation 4 has a reasonably good fit with experimentally observed thermal gradient and growth speed dependence (whether we use \(r_t\) values from Trivedi or Hunt-Lu).
Trunk diameters measured in quenched mushy-zone
(Al-Si alloys: $G_i=150$ K cm$^{-1}$, velocity = 43 μm s$^{-1}$)
Lines are predictions from Eq: 5 using $r_t$ (Trivedi)

Trunk diameters in the mushy-zone are greater than those expected from the Trunk diameter model, especially near the array tips.
Trunk diameter measured in quenched mushy-zone
(Al-Si alloys: $G_l=150$ K cm$^{-1}$, velocity = 156 μm s$^{-1}$)
Lines are predictions from Eq: 5 using $r_t$ (Trivedi)

Trunk diameters in the mushy-zone are greater than those expected from the Trunk diameter model.
Trunk diameter measured in quenched mushy-zone

(Al-Si alloys: $G_i=150$ K cm$^{-1}$, velocity = 43 μm s$^{-1}$)

Lines: Vary $r_t$ to obtain least-squared fit of the data to Eq: 5.

These $r_t$ values are larger than predicted from Trivedi/or Hunt-Lu models.
Trunk diameter measured in quenched mushy-zone

Al-Si alloys: Growth speed 156 μm s⁻¹

Lines: Vary $r_t$ to obtain least-squared fit of the data to Eq: 5.

These $r_t$ values are larger than predicted from Trivedi/or Hunt-Lu models.
The tip radii obtained by forcing a least squared fit of the observed trunk diameter vs. time data to the trunk-diameter coarsening equation are larger than the tip radii calculated from the Hunt-Lu or Trivedi models.

<table>
<thead>
<tr>
<th>C_o wt%</th>
<th>G_l K/cm</th>
<th>G_m K/cm</th>
<th>R μm/s</th>
<th>r_t-HL μm</th>
<th>r_t-Trivedi μm</th>
<th>r_t from best fit least squared analysis μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>150</td>
<td>106.4</td>
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<td>8</td>
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<td>150</td>
<td>150</td>
<td>156</td>
<td>1.58</td>
<td>1.99</td>
<td>2.29</td>
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</tbody>
</table>

Does natural convection during terrestrial directional solidification increase dendrite trunk diameter (dendrite tip radius?)
Comparison of microstructures: Al-7% Si directionally solidified on ground and on ISS (MICAST6)

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

**Terrestrial DS:**
15 K cm\(^{-1}\) →

Convection causes dendrite clustering (steepling) at low thermal gradient and growth speeds during terrestrial DS.
Comparison of microstructures: Al-7% Si directionally solidified on ground and on ISS (MICAST7)

MICAST7 SEED
41 K cm\(^{-1}\), 22 µm s\(^{-1}\)

MICAST7: 26 K cm\(^{-1}\)
21 µm s\(^{-1}\)
11 µm s\(^{-1}\)

Terrestrial DS:
24 K cm\(^{-1}\)

23 µm s\(^{-1}\)
10 µm s\(^{-1}\)
Primary dendrite trunk diameter as compared to trunk diameter model calculations, using $r_t$ (Trivedi)

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.
ISS samples show better agreement with calculations from the models than terrestrial samples (primary dendrite arm spacing and trunk diameter)

<table>
<thead>
<tr>
<th>Trivedi</th>
<th>ISS-samples</th>
<th>Terrestrial (no steepling)</th>
<th>Terrestrial (steepling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary dendrite arm spacing/calculated from model</td>
<td>0.945± 0.0833</td>
<td>0.791± 0.0931</td>
<td>0.695± 0.223</td>
</tr>
<tr>
<td>Primary dendrite trunk diameter/calculated from model</td>
<td>1.069± 0.0361</td>
<td>1.113± 0.0890</td>
<td>1.513± 0.560</td>
</tr>
</tbody>
</table>
Natural convection decreases primary dendrite arm spacing and increases primary dendrite trunk diameter in Al-26.5 % Cu


Al-26.5 wt% Cu, 30 K cm⁻¹, 4.2 μm s⁻¹
Al-26.5 wt% Cu, 25 K cm⁻¹, 4.2 μm s⁻¹
Al-26.5 wt % Cu, 30 K cm⁻¹, 4.2 μm s⁻¹

Terrestrial: Solutally stable, thermally stable mode
Terrestrial: Solutally unstable, thermally stable mode
Microgravity:

Primary spacing ➔ 450 ± 20 μm
√(A/(N-1))

Trunk diameter ➔ 120 ± 18 μm

340 ± 10 μm

122 ± 18 μm

1540 ± 10 μm

92 ± 11 μm
Conclusions

• Primary dendrite trunk diameters in a range of Al-Si alloys directionally solidified under varying thermal gradients and growth speeds shows a reasonable fit with a simple analytical model (based on Kirkwood’s approach) proposed here.

• Primary dendrite trunk diameters of Al-7 wt% Si alloy directionally solidified on the ISS show a very good fit with the analytical model.

• Natural convection which causes radial in-homogeneity (dendrite clustering) in these alloys appears to increase primary dendrite trunk diameter.
  – decreases primary dendrite arm spacing.
Acknowledgments

• NASA
• ESA
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• Robert E. Erdmann - The of Arizona
• Ravi S. Rajamure - MS: Cleveland State University
Microgravity Processing: Partially remelt and then DS from terrestrially grown dendritic mono-crystal in μg.

(AI-7%Si Single Crystal Dendritic)

Transverse View

ESA: Sample Cartridge Assembly

ESA_MSL Low Gradient Furnace

NASA_MSSR-1 Flight Rack
Terrestrial processing
Graphite crucible (~9 mm ID, ~19 mm OD), $10^{-4}$ torr vacuum

Thermal Gradient at the liquidus temperature
(Al-7%Si, Graphite Crucible, 3 TCs located along crucible length)

![Graph showing thermal gradient](image)

- TC1: 4.2 μm s⁻¹
- TC2: 4.2 μm s⁻¹
- TC3: 85 μm s⁻¹

Temperature, °C
Translation Distance, cm

$G_l = 42$ K cm⁻¹
$G_l = 43$ K cm⁻¹
Microgravity Processed Sample MICAST 7

X-ray radiograph of MICAST7

Eutectic Melt Back / Isotherm

MICAST7 Directionally solidified Al-7 wt% Si alloy

Reaction

No reaction

Alumina-1

Eutectic Melt Back

Alumina crucible
MICAST6: ESA-Low Gradient Furnace (1-hr heat-up, 5-hr hold, $G_i \sim 20$ 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, $G \approx 20$ K cm$^{-1}$): 3.8 cm at 5 $\mu$m s$^{-1}$, 11.3 cm at 50 $\mu$m 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.
MICAST7: ESA-SQF (1-hr heat-up, 1-hr hold ($G_1 \sim 26 \text{ K cm}^{-1}$)):  
8.4 cm at 20 $\mu$m s$^{-1}$, 6.5 cm at 11 $\mu$m s$^{-1}$

![Graph showing temperature gradients at nominal liquidus and solidus isotherms.](image)
MICAST7: ESA-SQF (1-hr heat-up, 1-hr hold ($G_l \sim 26$ K cm$^{-1}$)):
8.4 cm at 20 $\mu$m s$^{-1}$, 6.5 cm at 11 $\mu$m s$^{-1}$
Growth conditions for MICAST6 and MICAST 7 transverse microstructures examined

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$G_I$, K cm$^{-1}$</th>
<th>$G_m$, K cm$^{-1}$</th>
<th>$R$, μm s$^{-1}$</th>
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