MS&T2012: “Solidification, Crystal Growth and Microstructural Correlation with Properties of Materials: To Celebrate 75th Birthday of Prof. Martin E. Glicksman “

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

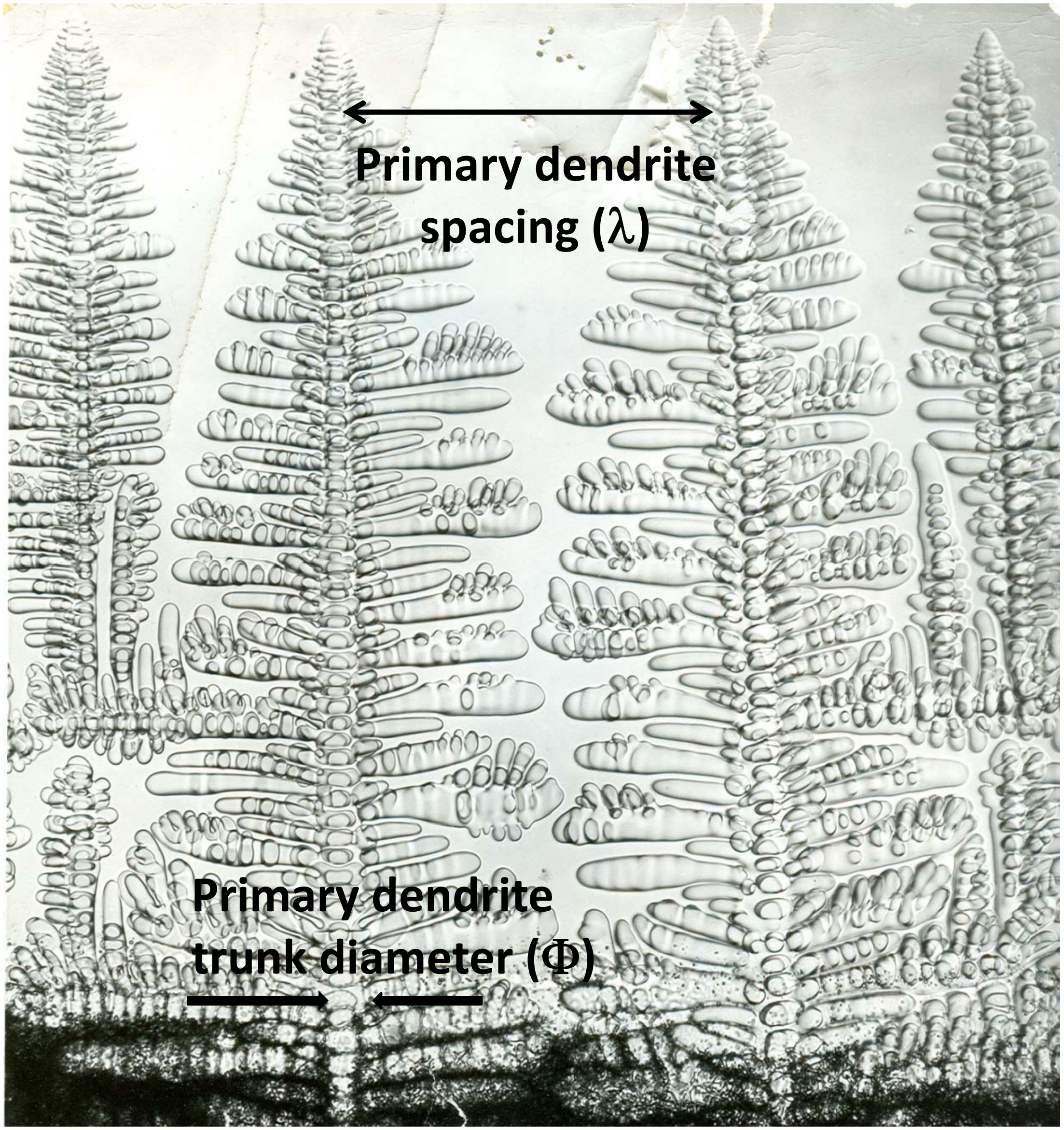
(Microstructure Formation in Castings of Technical Alloys under Diffusive and Magnetically Controlled Convective Conditions)

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.

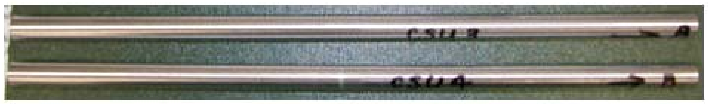
Advantages:	Minimize Thermo-Solutal Convection
Intent:	Produce Segregation Free Samples Grown Under Diffusion-Controlled Conditions
Purpose:	Better Understand the Relationship between Processing and Microstructure-Development

Dendritic array morphology depends upon DS processing parameters: G_l, R, C_o, *Convection*

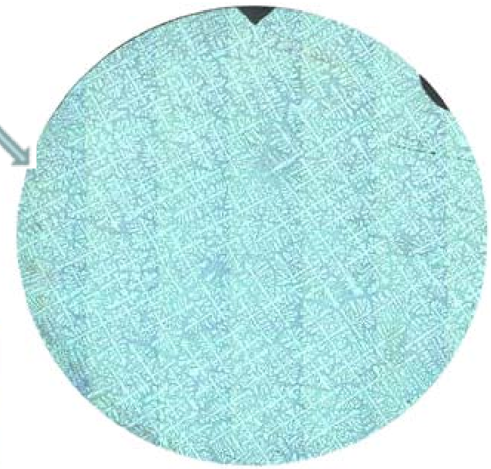


1. Primary dendrite arm spacing (λ): Extensive literature (SCN/Metals)
2. Secondary/tertiary arm spacing: Extensive-SCN/Metals
3. Dendrite tip radius: SCN/ limited (Al-Cu, Pb-Au, Pb-Pd)
4. Primary dendrite trunk diameter (Φ): Limited (Esaka:Thesis-86, Grugel: 92/95)

Microgravity Processing : Partially remelt and then DS from terrestrially grown dendritic mono-crystal in μg.



(Al-7%Si Single Crystal Dendritic)



Transverse View

ESA- Sample Cartridge Assembly

ESA_MSL Low Gradient Furnace

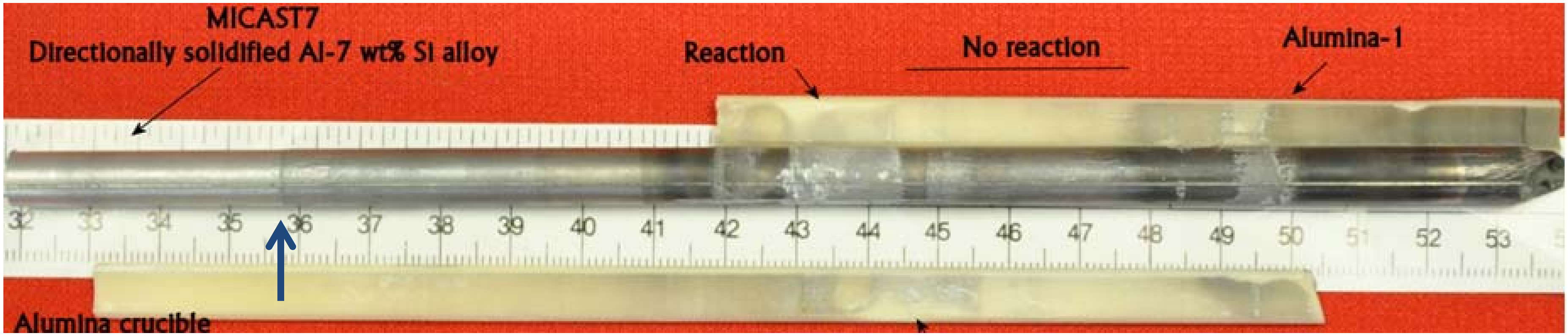
ESA:
Material
Science
Laboratory

NASA_MSSR-1 Flight Rack

Microgravity Processed Sample MICAST 7

Eutectic Melt Back / Isotherm

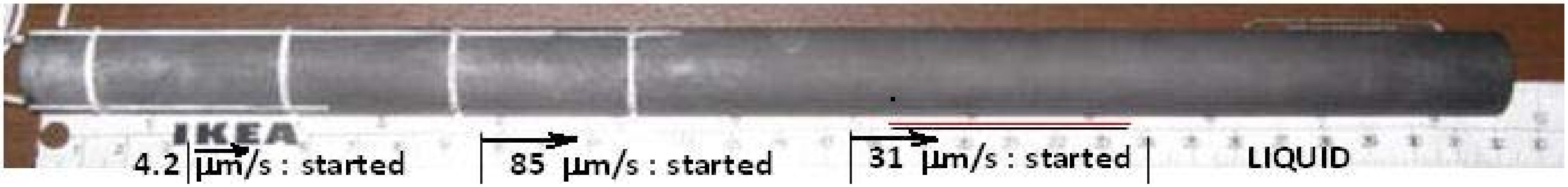
X-ray radiograph of MICAST7

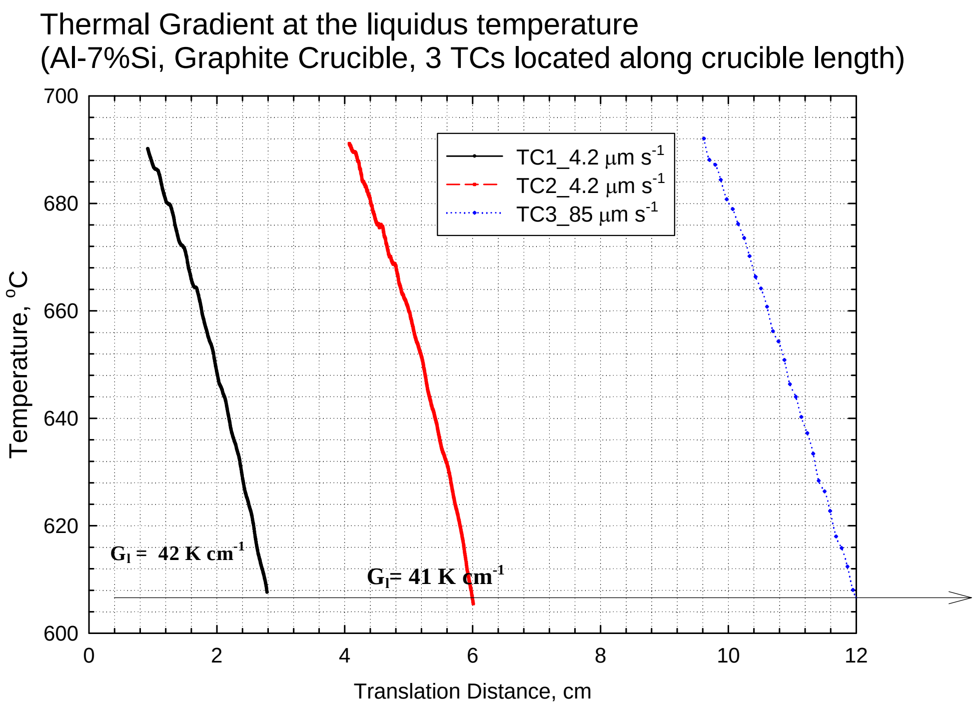


Eutectic Melt Back

Terrestrial processing

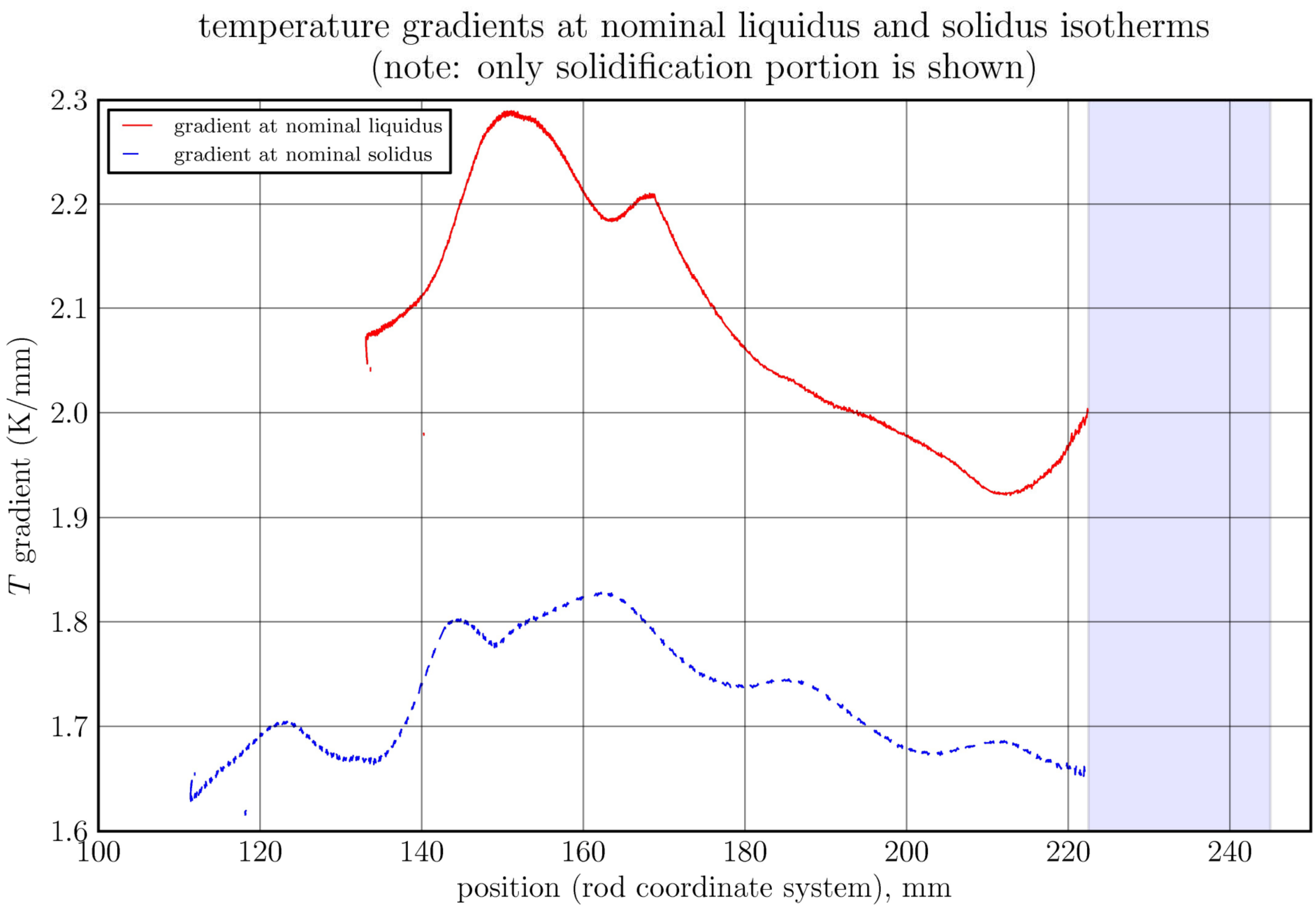
Graphite crucible (~9 mm ID, ~19 mm OD), 10^{-4} torr vacuum





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~ 20 K cm^{-1}): 3.8 cm at 5 μm s^{-1}, 11.3 cm at 50 μm s^{-1}



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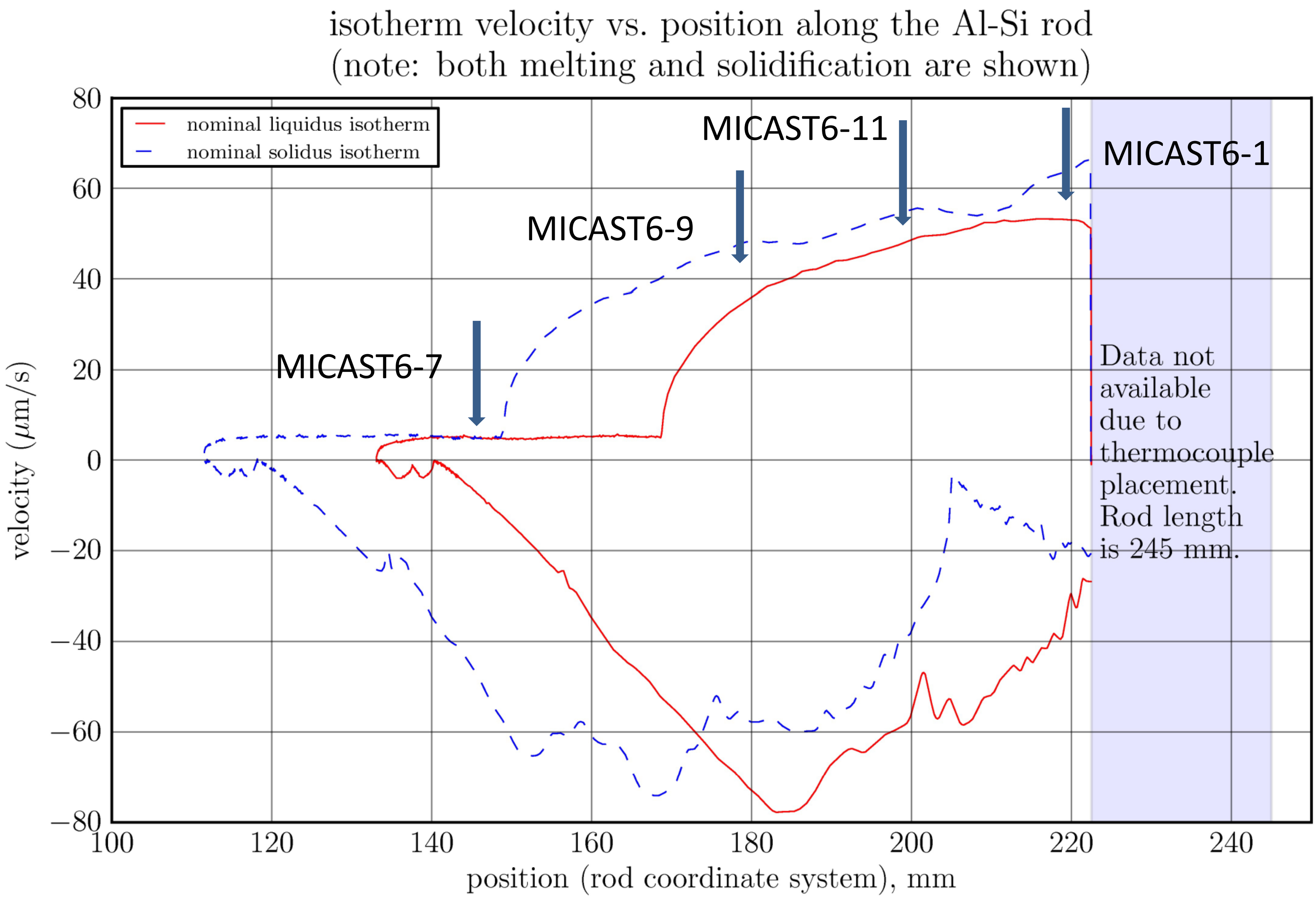
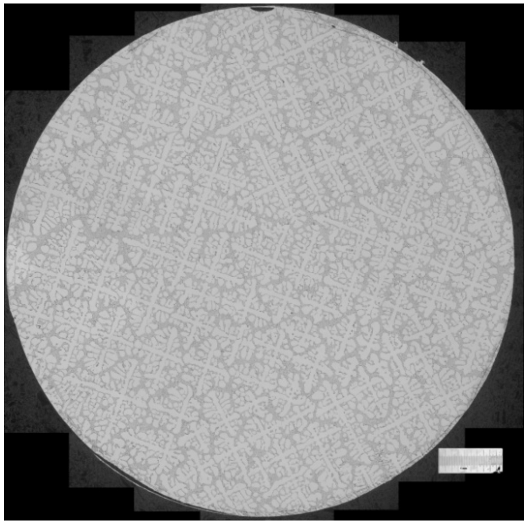


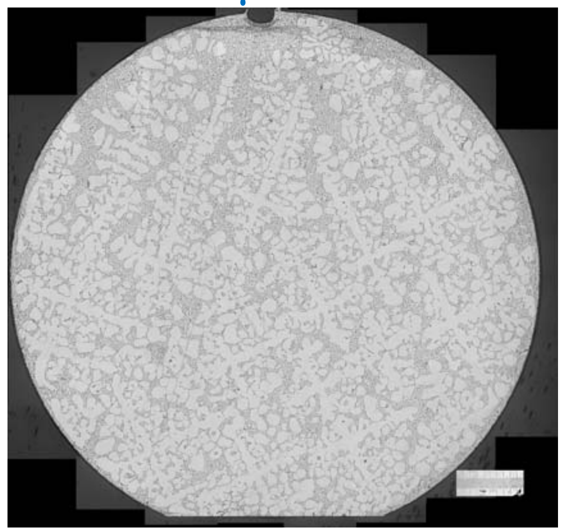
Comparison of microstructures: Al-7% Si directionally solidified on ground and on ISS (MICAST6)

MICAST6 SEED
41 K cm^{-1}, 22 μm s^{-1}

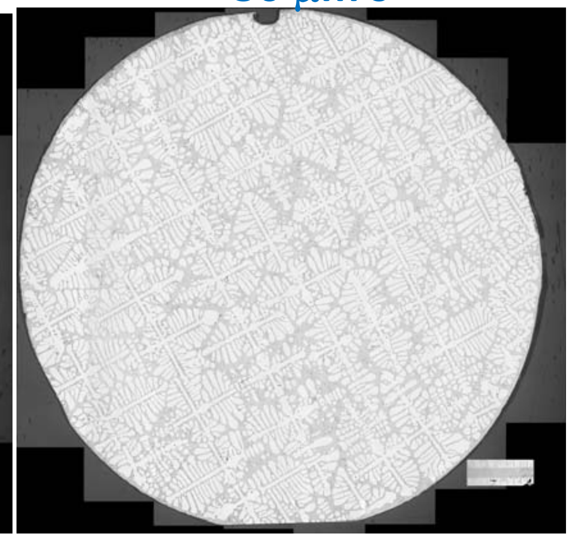


MICAST6: 20 K cm^{-1}

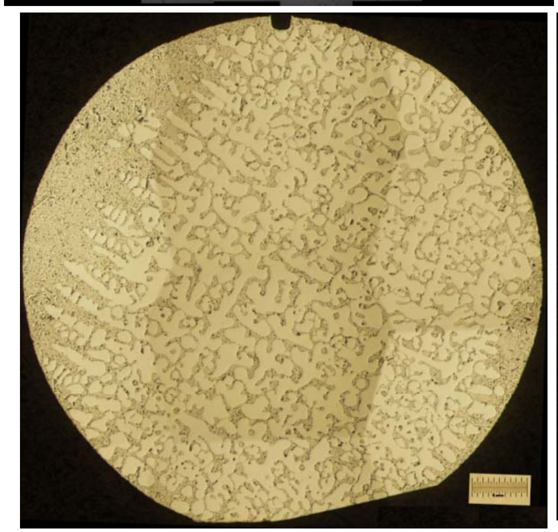
5 μm s^{-1}



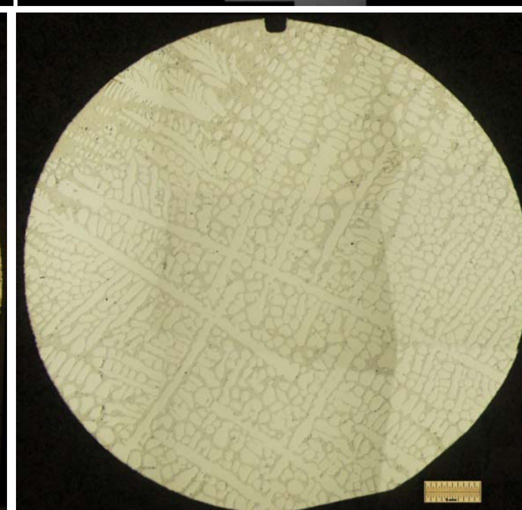
50 μm s^{-1}



Terrestrial DS:
15 K cm^{-1} ➔



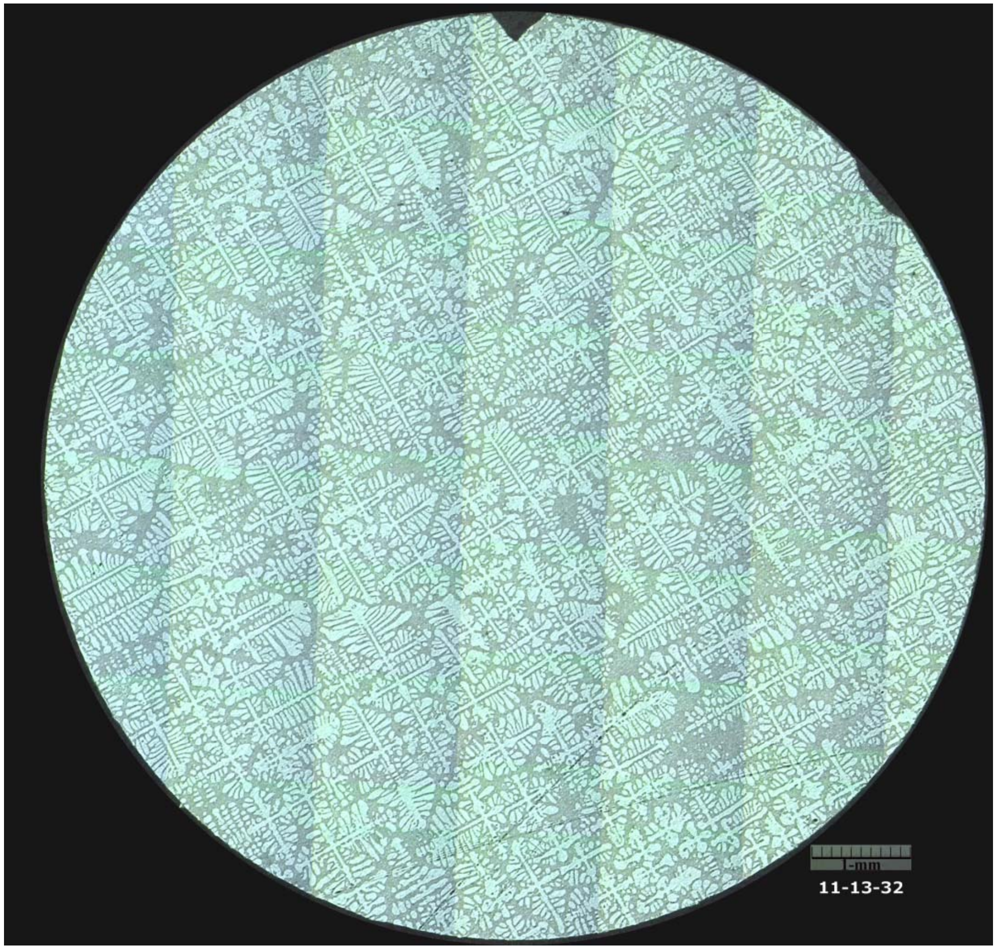
5 μm s^{-1}

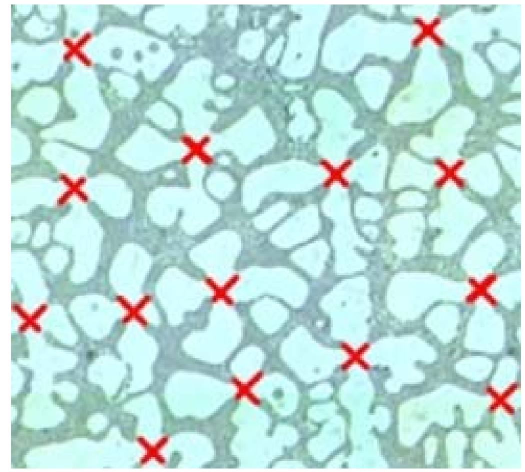


50 μm s^{-1}

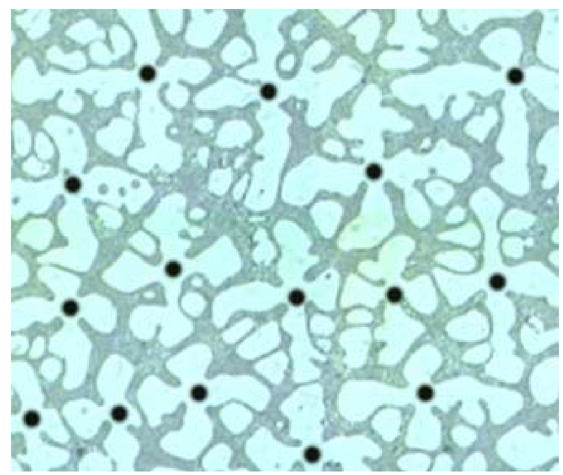
Convection causes dendrite clustering (steepling) at low thermal gradient and growth speeds during terrestrial DS.

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



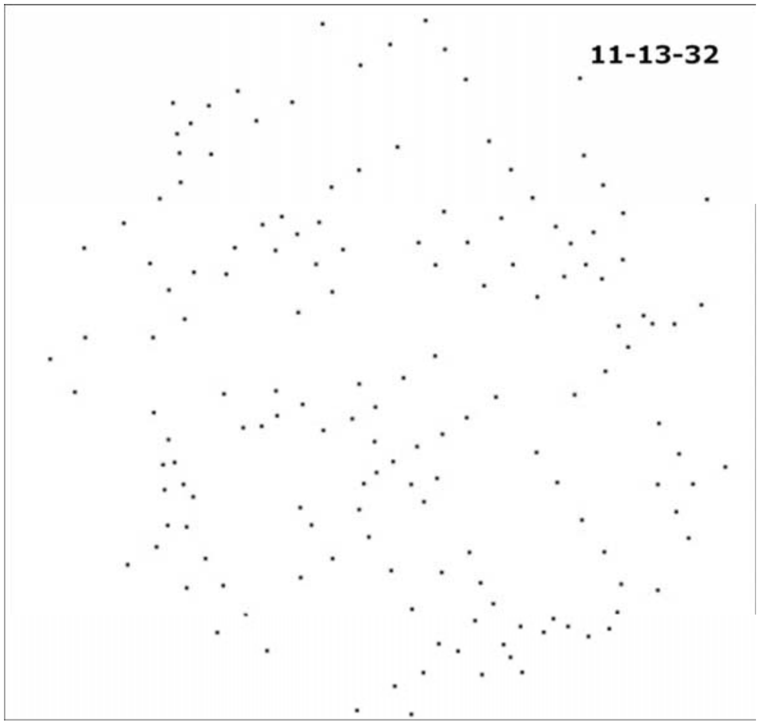


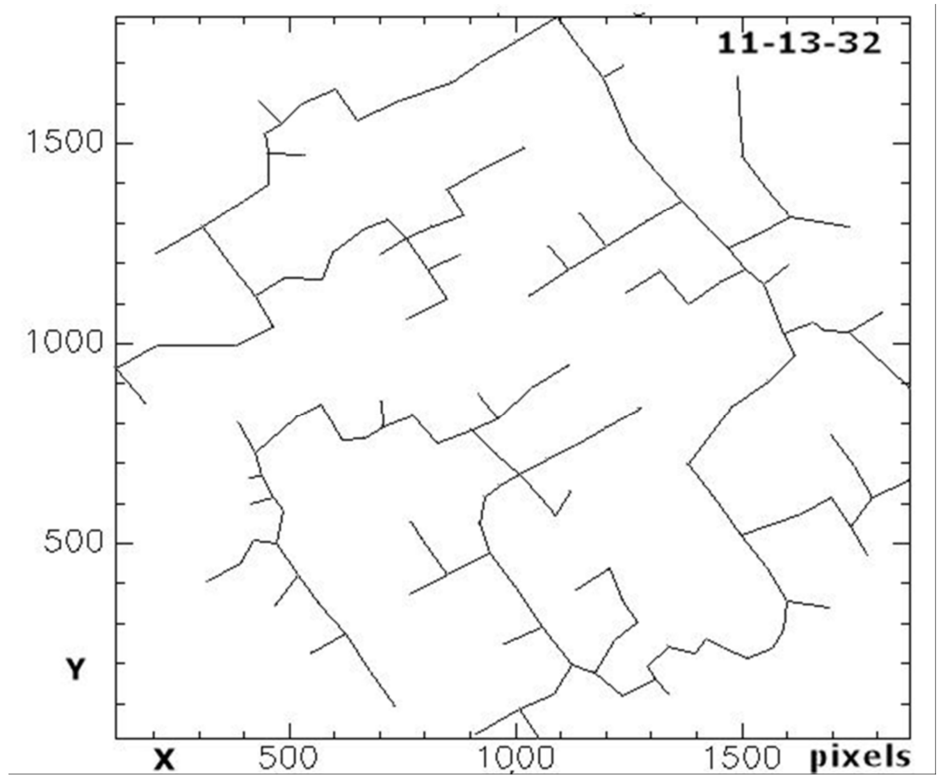
Primary dendrite trunk diameter



Primary dendrite arm spacing???

Which primary dendrite arm spacing to use?





Primary spacing ($\sqrt{A/(N-1)}$) = 623 μm

MST spacing= 412 ±138 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

$(m_l G_c^t - G_t)/(4\Pi^2 \Gamma T_m/r_t^2) = 1$ for small $R r_t/2D_l$

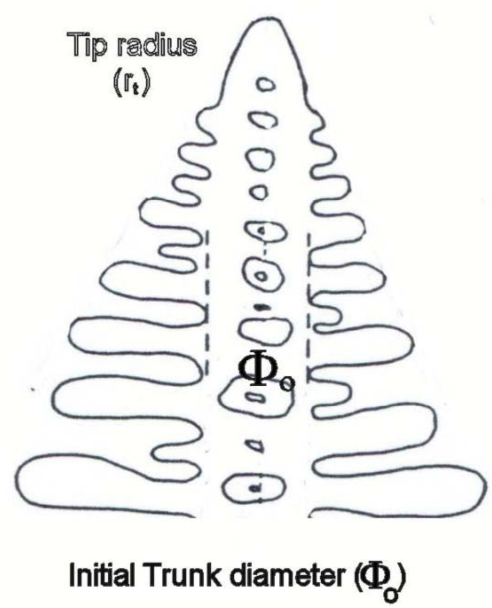
$$r_t = -\frac{G_L \lambda_1^2}{4\sqrt{2}[m_L C_t(1-k) + \frac{D_L G_L}{R}]}$$

	Analytical	Numerical
Tip radius:	Trivedi (1980)	Hunt-Lu (1996)
Primary spacing:	Trivedi (1984)	Hunt- Lu (1996)
Trunk diameter:	None	

Physical Properties for Al- 7 wt% Si

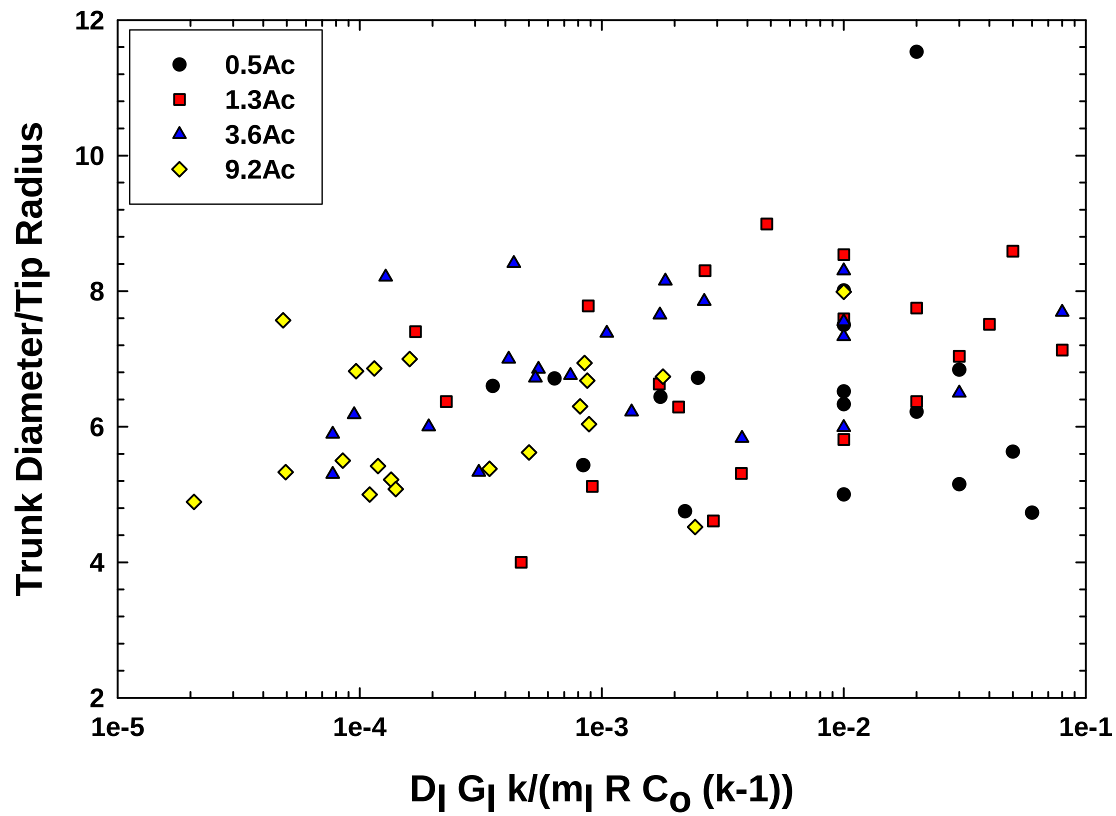
Co	7 wt% Si	
m_l	-6.31 K/ wt% Si	Metals Handbook, vol 8(1973)
k	0.1	
Γ	0.196 μm K	Gunduz and Hunt (1985)
D_l	$4.3X10^{-9}$ m²/s	(Poirier compilation)

Primary dendrite trunk diameter (ϕ)



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

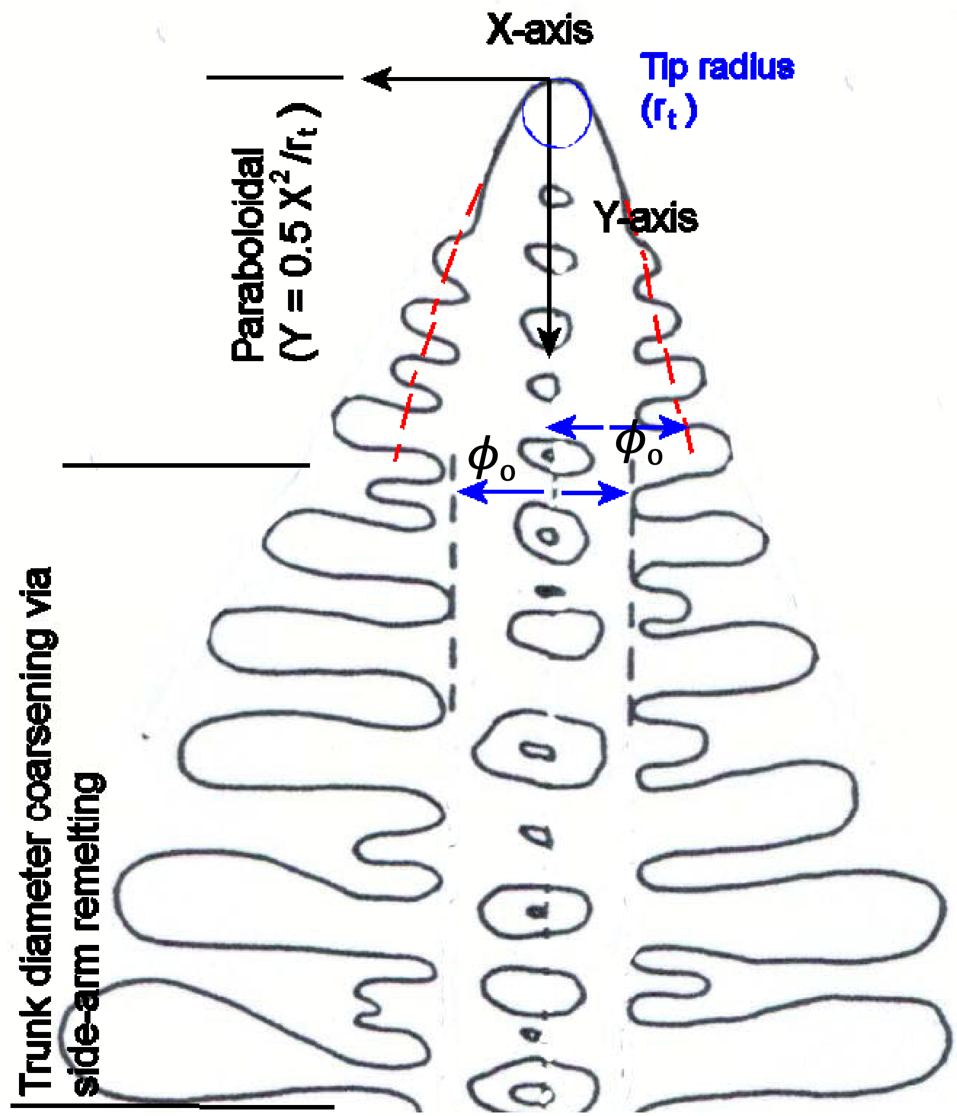
$D_l G_l k/(m_l R C_o (k-1))$]: More branched dendritic morphologies will be located towards the left, and less-branched/cellular towards the right side of the X-axis.



(Initial trunk diameter (ϕ_o)/tip radius) = 6.59±1.3

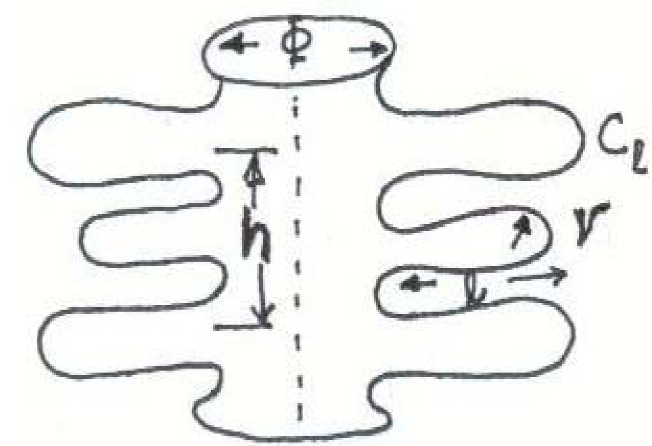
Primary dendrite trunk diameter (ϕ) model

1. The trunk diameter (ϕ) increases rapidly near the tip till time, **t_o= 22*r_t/R)**, when $\phi = \phi_o$ = **6.59 r_t** (paraboloidal envelope near tip).



Primary dendrite trunk diameter (ϕ) 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” = ϕ.



Assumptions:

1. Kirkwood model (1985) of ripening applies.
2. Secondary arm melts back because of its curvature.
3. Mass of the melted arm deposits on trunk surface where there is negative curvature.

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

$$\pi\phi h\,\frac{d\phi}{2\,dt} = 4 * \pi r^2\,\frac{dl}{dt} \qquad (2)$$

$$C_l = C_o + R\,G_m\,t/m_l \qquad (3)$$

$$\phi^2\,\frac{d\phi}{dt} = 32\,\frac{D_l\,\Gamma}{m_l\,(1-k)\left(C_o + \frac{R\,Gm\,t}{m_l}\right)} \qquad (4)$$

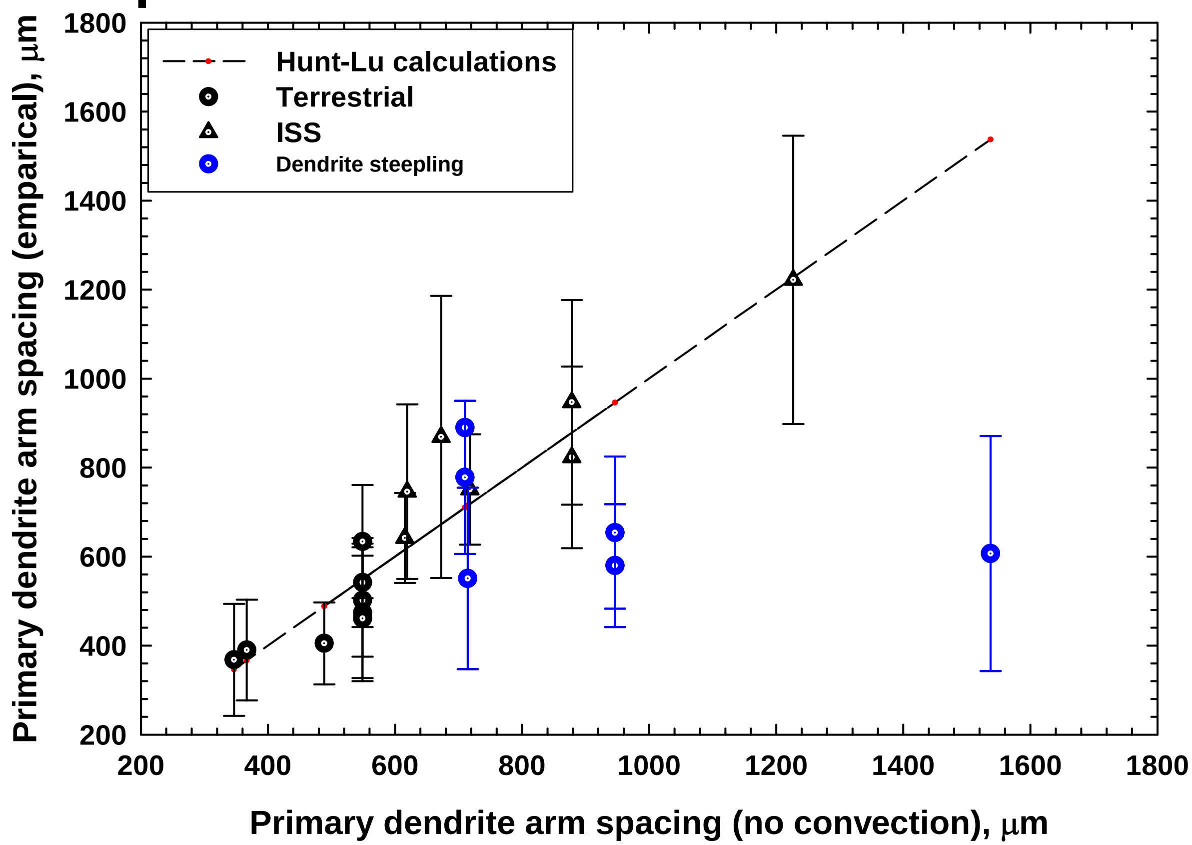
Primary dendrite trunk diameter (ϕ) model

$$\phi^3 = 96 \frac{D_l \Gamma}{RGm\ (1-k)} \ln\left\{\frac{\left(1 + \frac{R\,Gm\ t}{m_l C_o}\right)}{\left(1 + \frac{R\,Gm\ t_o}{m_l C_o}\right)}\right\} + \Phi_o^3$$

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

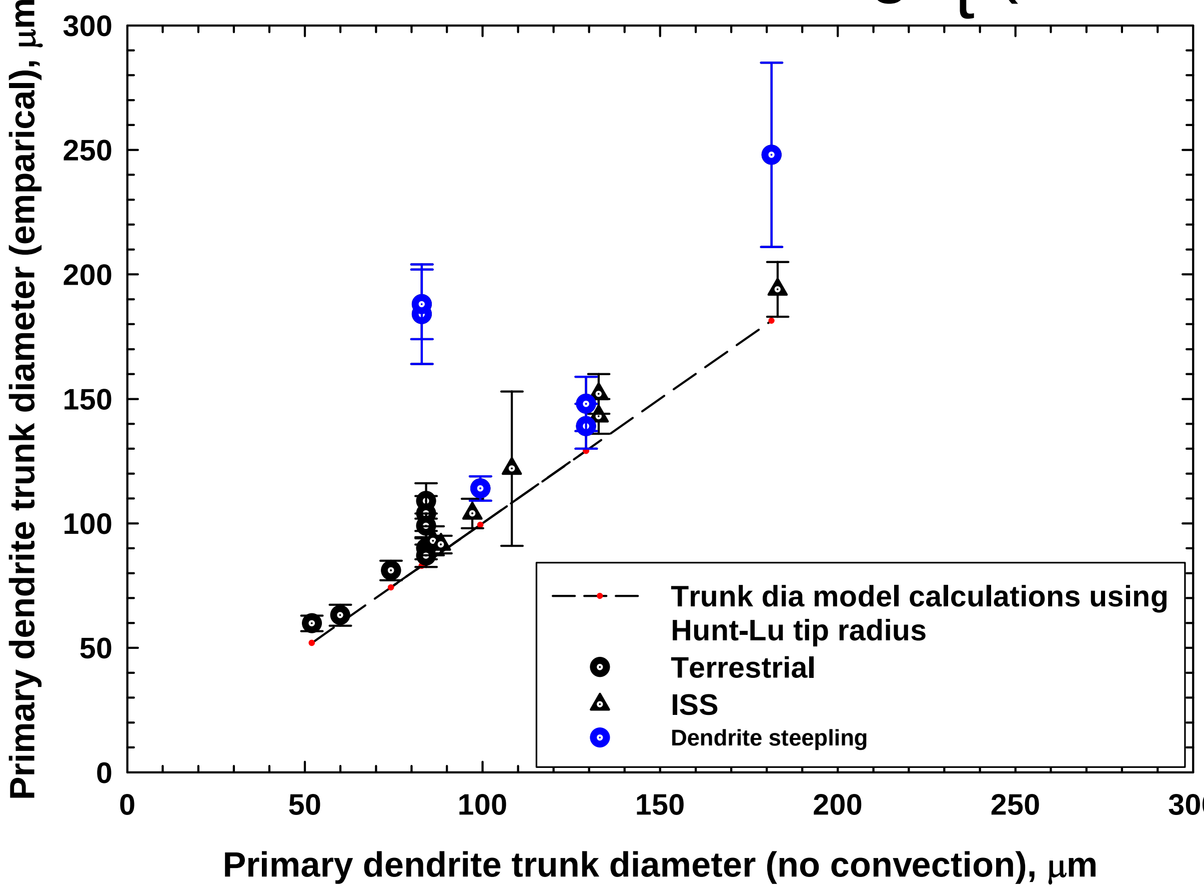
Use tip radius (r_t) predicted from Trivedi (1980) or Hunt-Lu (1996) models to get the initial trunk diameter ϕ_o = 6.59 r_t in order to predict the processing parameter dependence of "Primary dendrite trunk diameter" from above relationship.

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 <u>increases</u> 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 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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- ESA
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