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

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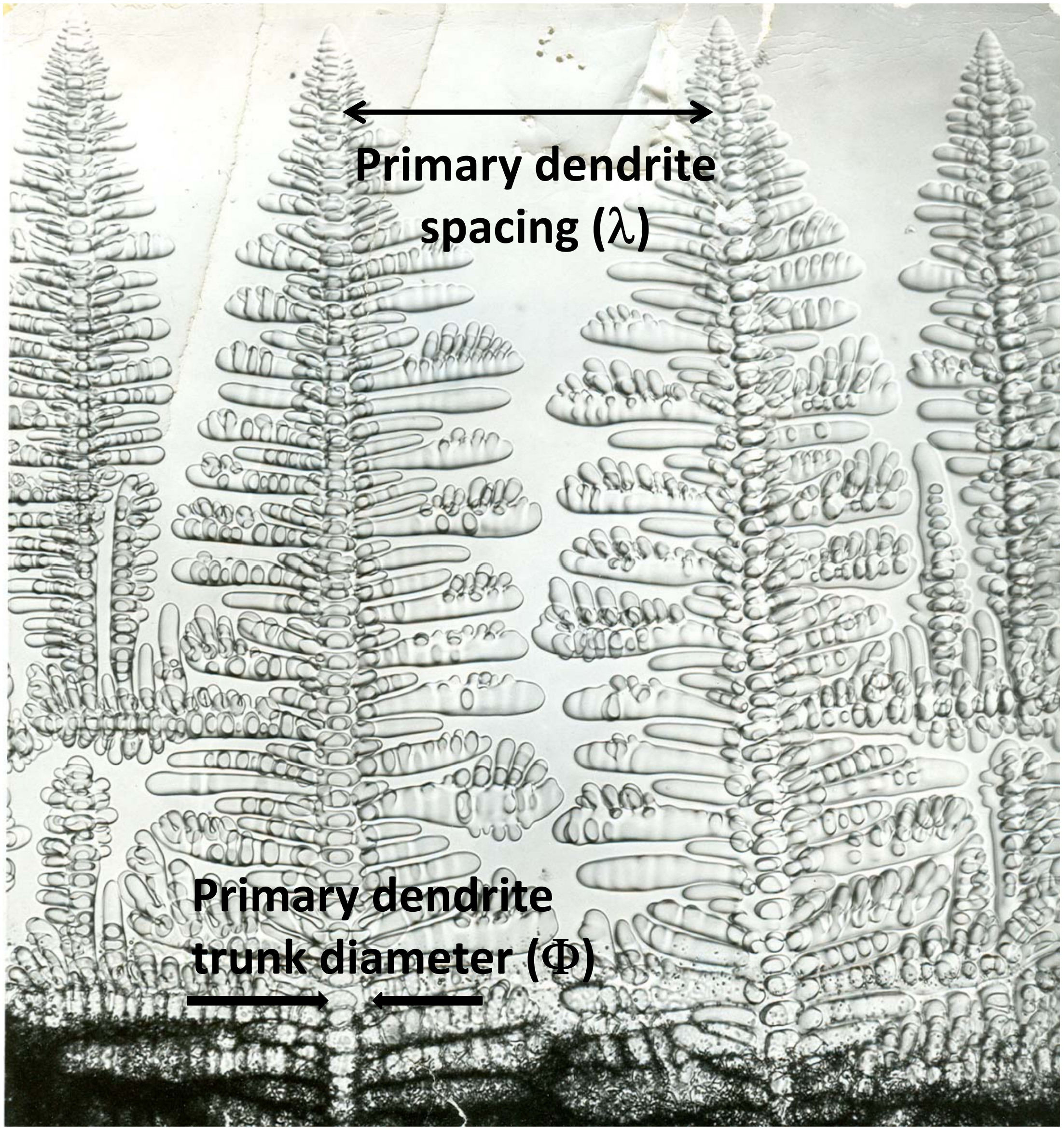
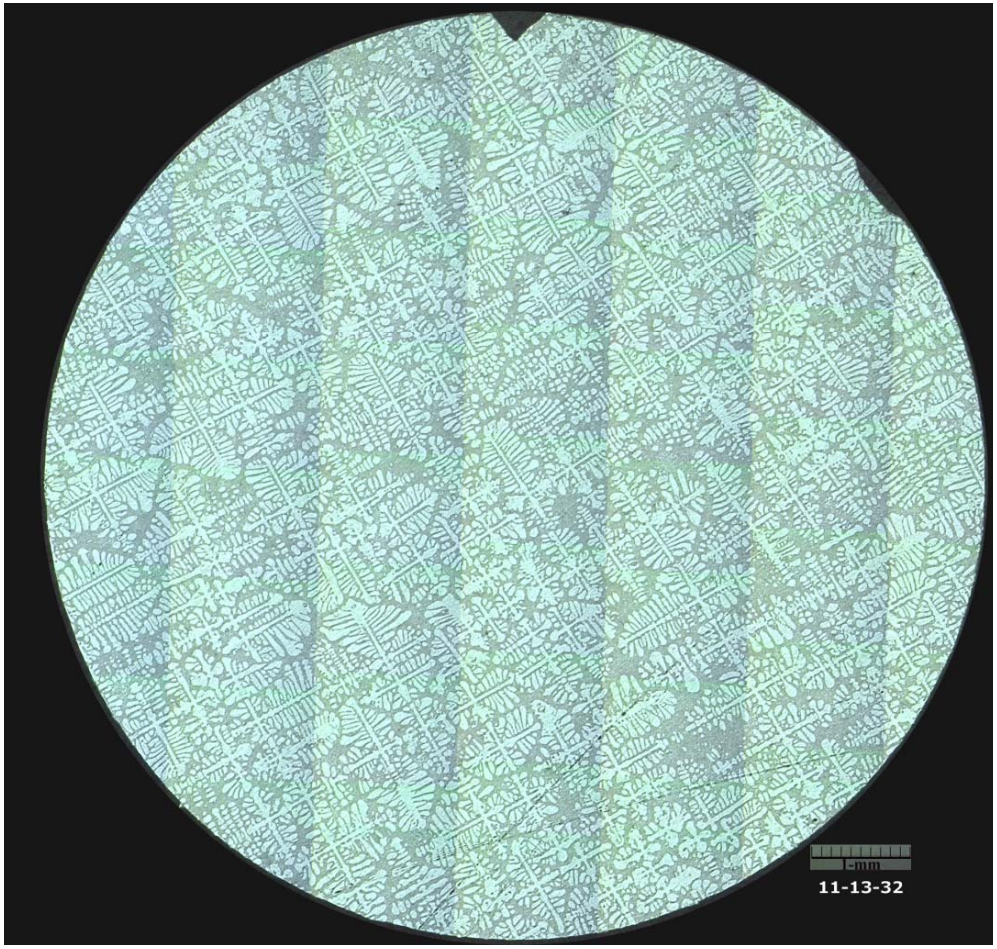
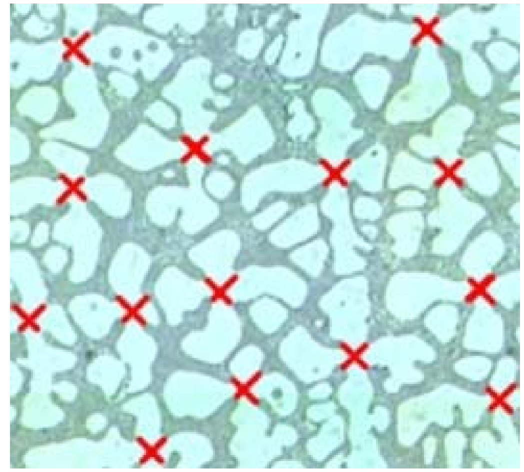
Dendritic array morphology depends upon DS processing parameters: G_l, R, C_o, *Convection*



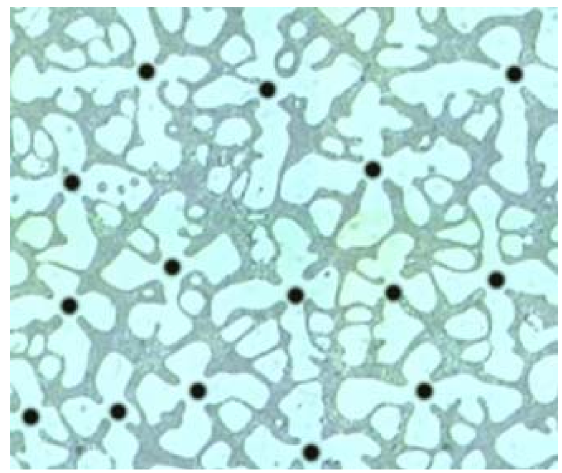
1. Primary dendrite arm spacing (λ): Extensive literature (SCN/Metals)
2. Secondary/tertiary arm spacing: Extensive-SCN/Metals
3. Dendrite tip radius: SCN/ limited (Al-Cu, Pb-Au, Pb-Pd)
4. Primary dendrite trunk diameter (Φ): Limited (Esaka:Thesis-86, Grugel: 92/95)

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



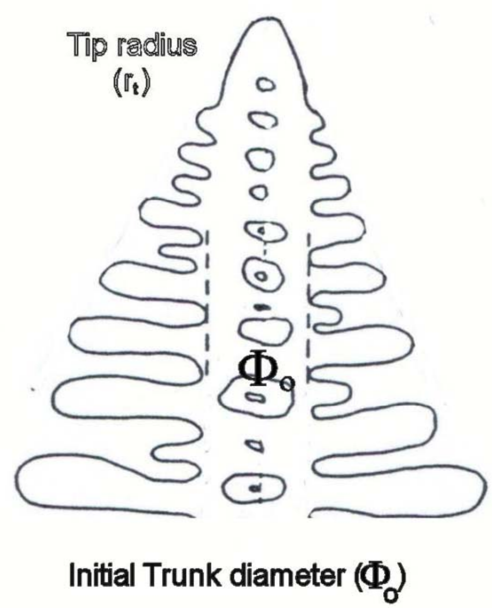


Primary dendrite trunk diameter

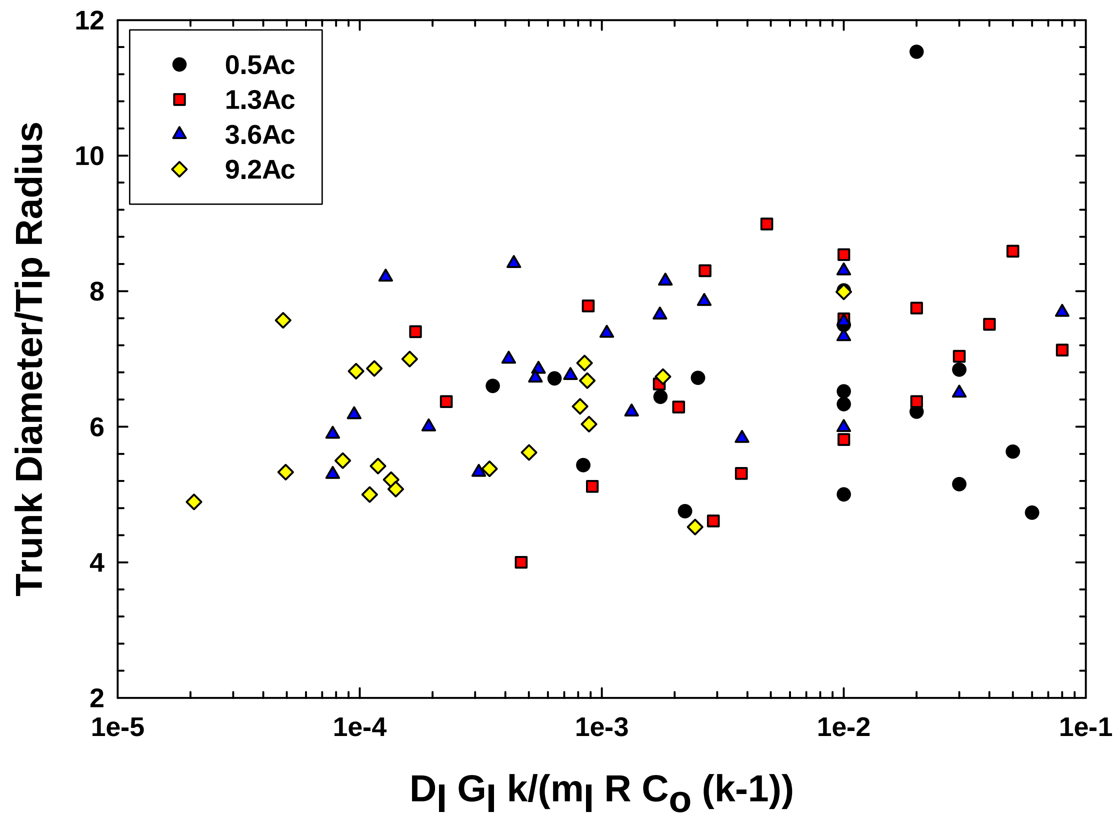


Primary dendrite arm spacing???

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)

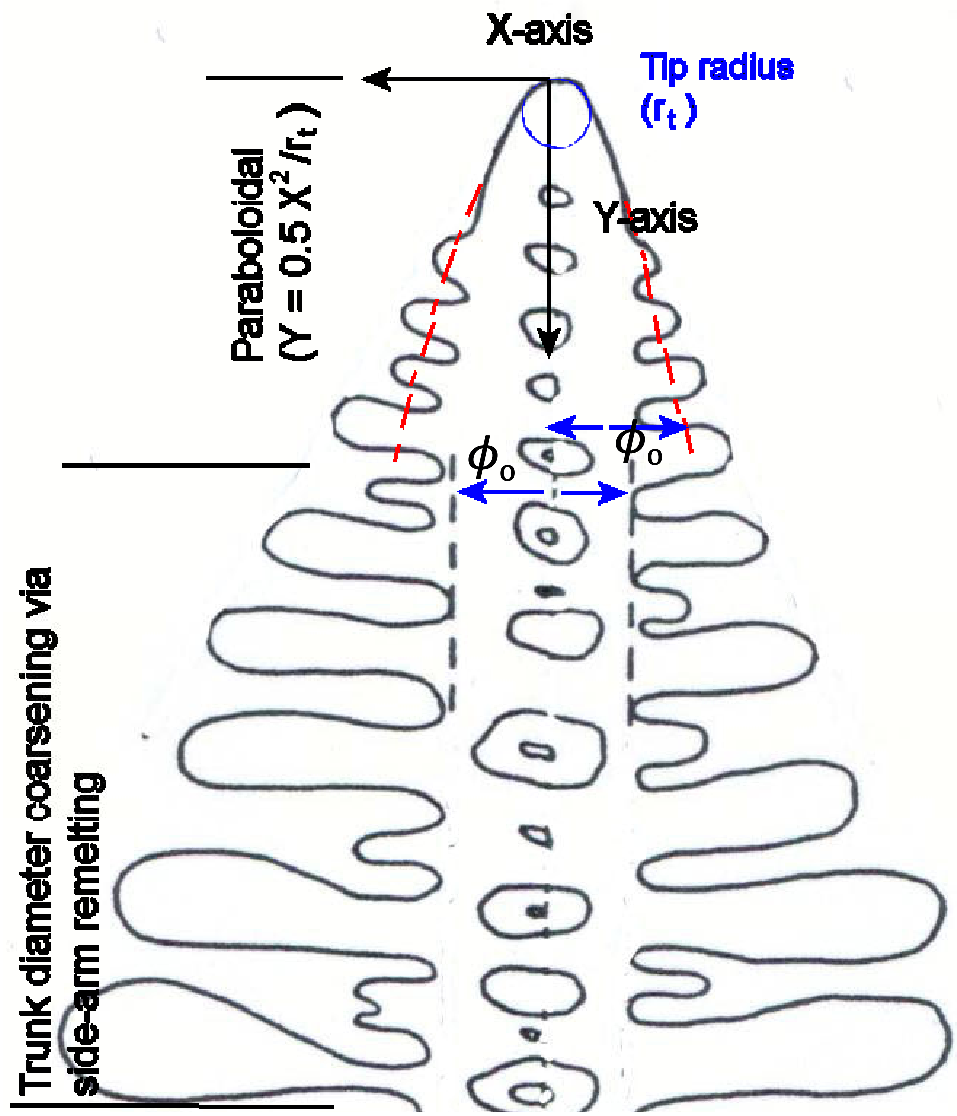


$D_l G_l k/(m_l R C_o (k\text{-}1))$]: More branched dendritic morphologies will be located towards the left, and less-branched/cellular towards the right side of the X-axis.

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

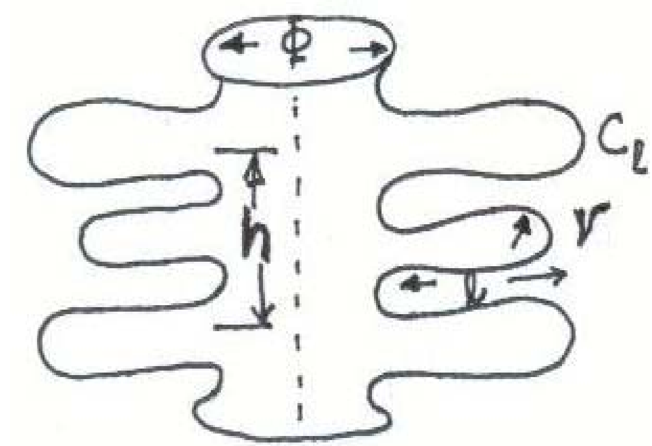
Primary dendrite trunk diameter (ϕ) model

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.

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

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

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

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

Primary dendrite trunk diameter (ϕ) model

$$\phi^3 = 96 \frac{D_l \Gamma}{RGm\ (1-k)} \ln\left\{\frac{\left(1+\frac{R\,Gm\ t}{m_l C_o}\right)}{\left(1+\frac{R\,Gm\ t_o}{m_l C_o}\right)}\right\} + \Phi_o^3 \qquad (5)$$

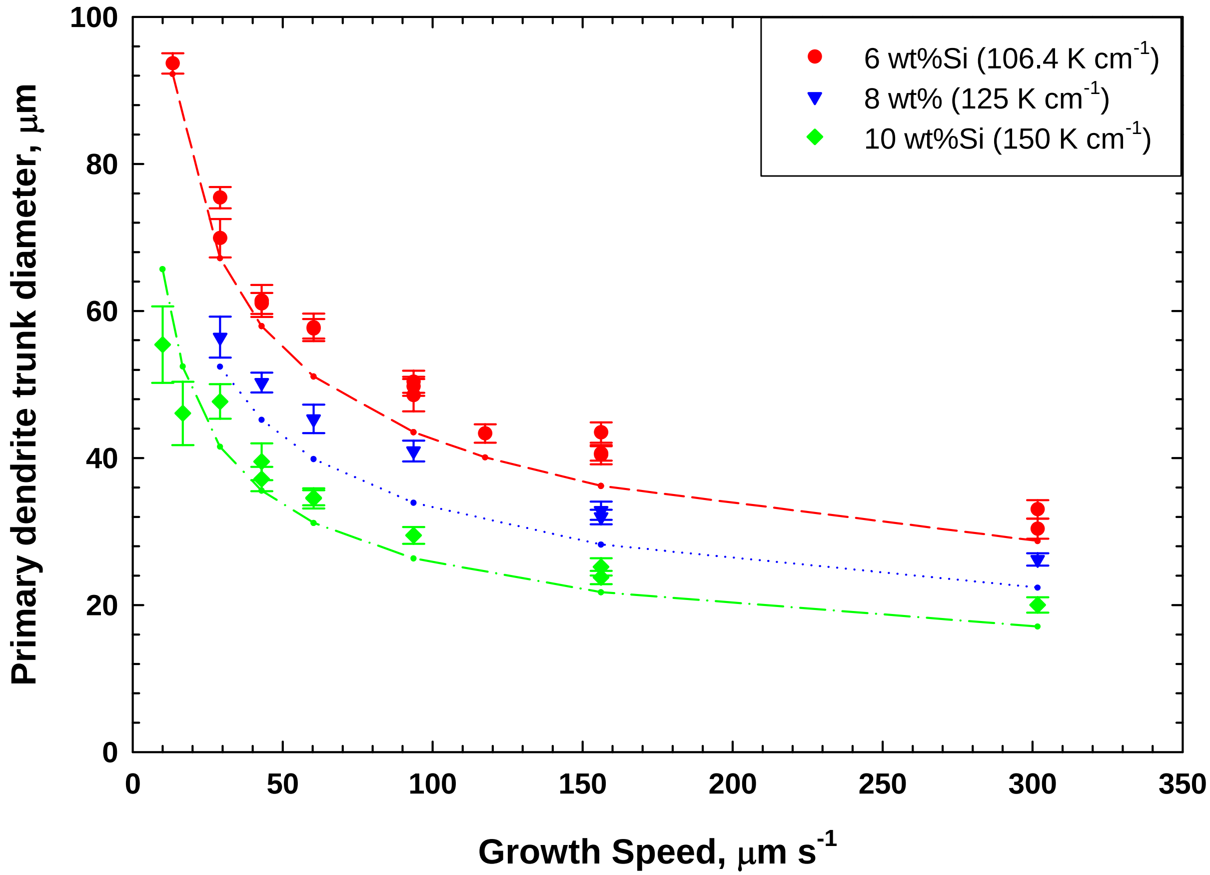
Mushy zone freezing time $\sim$ $m_l(C_E\text{-}C_o)/RG_m$

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 trunk diameter

Lines are predictions from Eq: 5 using $\mathbf{r_t}$ (Trivedi)

(G_l=150 K cm^{-1}, G_{mush} (listed in brackets))

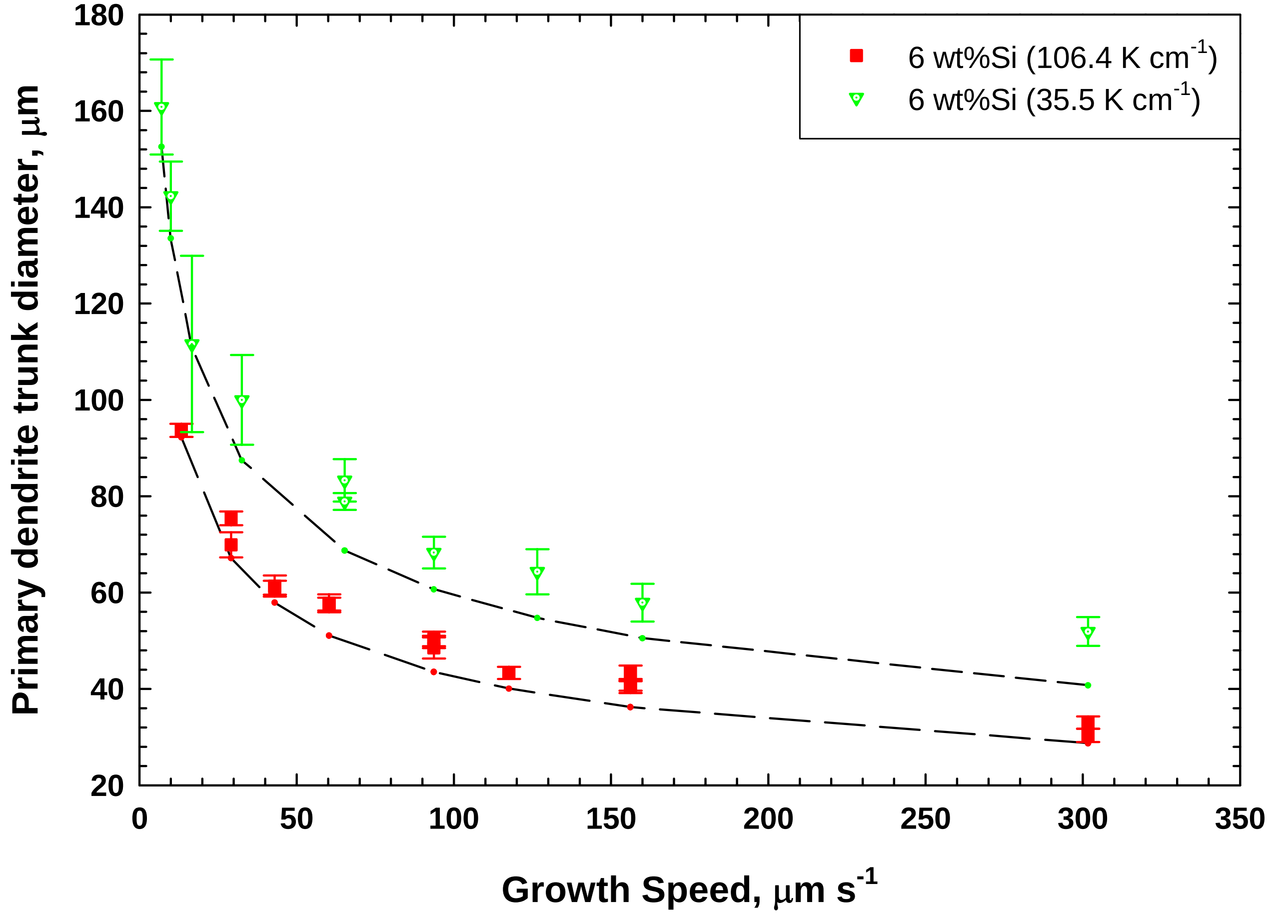


Equation 4 has a reasonable fit with experimentally observed solute content and growth speed dependence (whether we use $\mathbf{r_t}$ predictions from Trivedi or Hunt-Lu).

Primary dendrite trunk diameter (Al-6wt% Si)

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

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

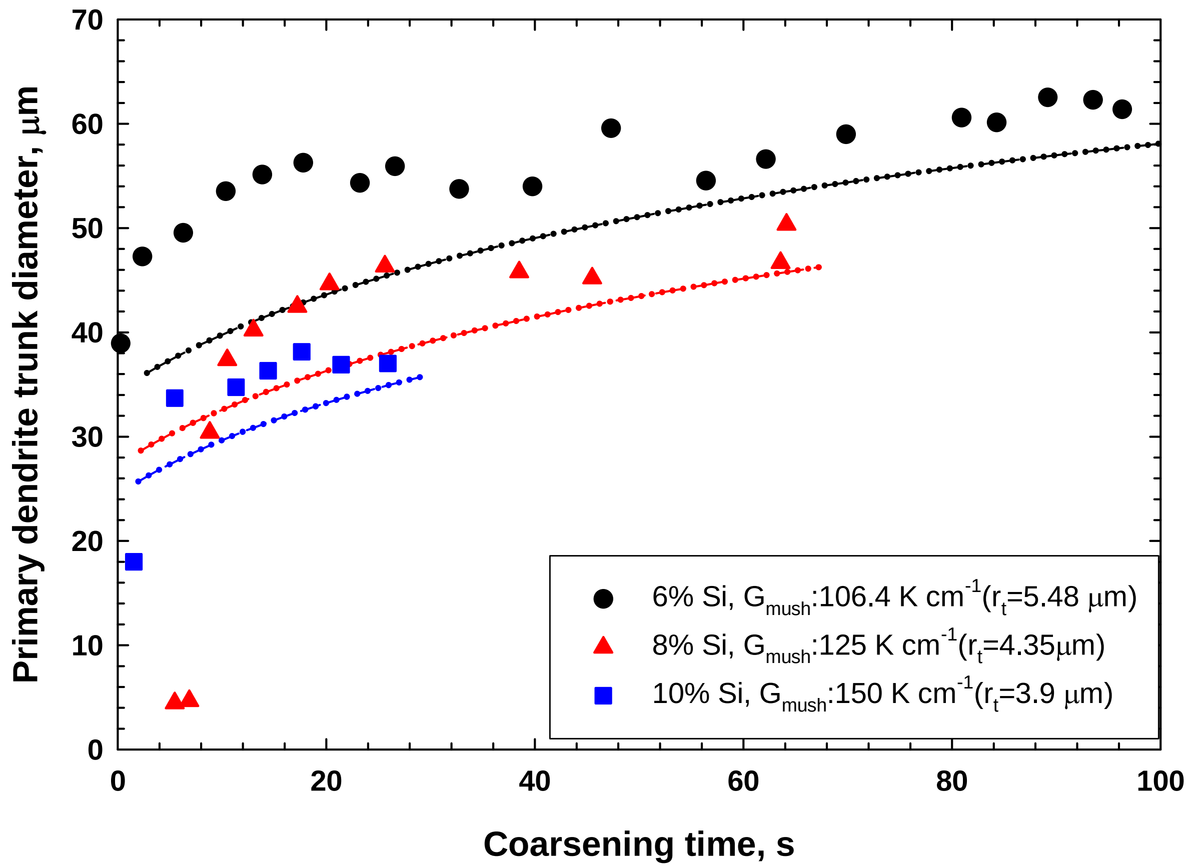


Equation 4 has a reasonably good fit with experimentally observed thermal gradient and growth speed dependence (whether we use $\mathbf{r_t}$ values from Trivedi or Hunt-Lu).

Trunk diameters measured in quenched mushy-zone

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

Lines are predictions from Eq: 5 using $\mathbf{r_t}$ (Trivedi)

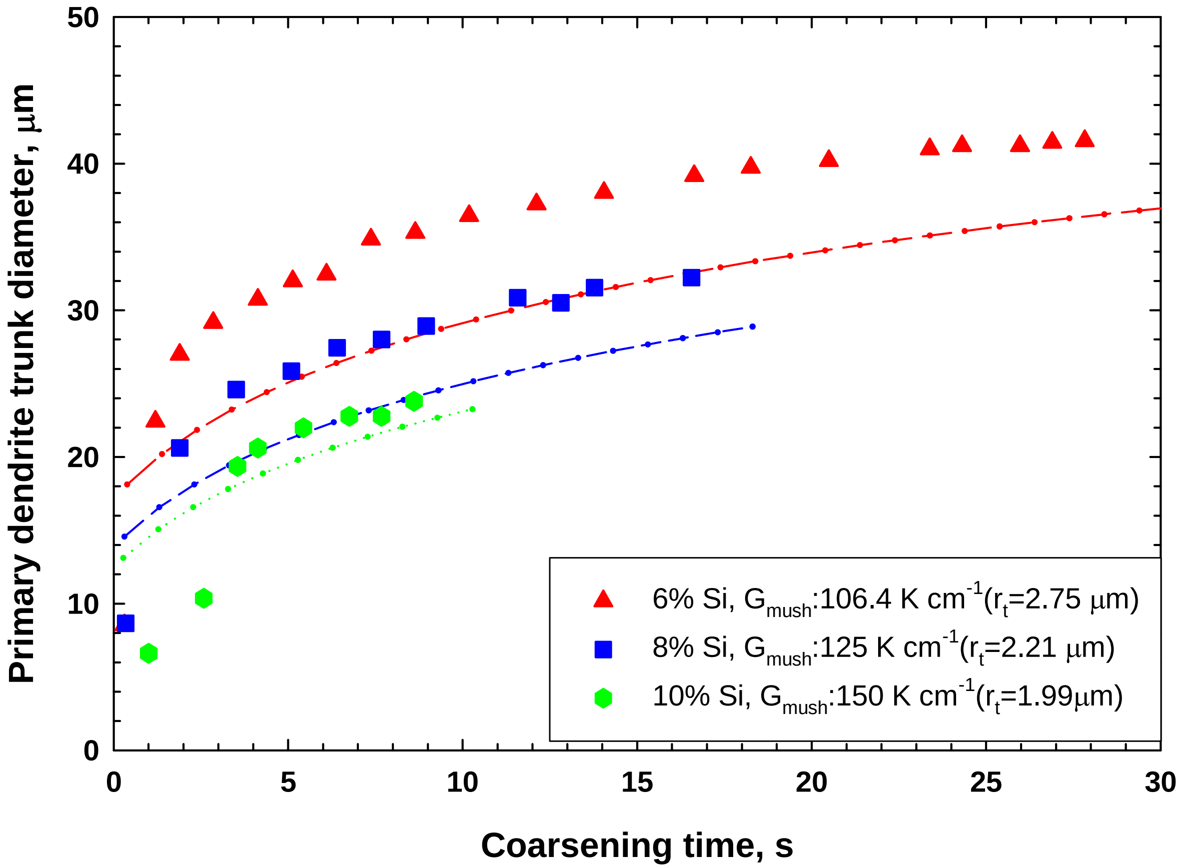


Trunk diameters in the mushy-zone are greater than those expected from the Trunk diameter model, especially near the array tips.

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 $\mathbf{r_t}$ (Trivedi)

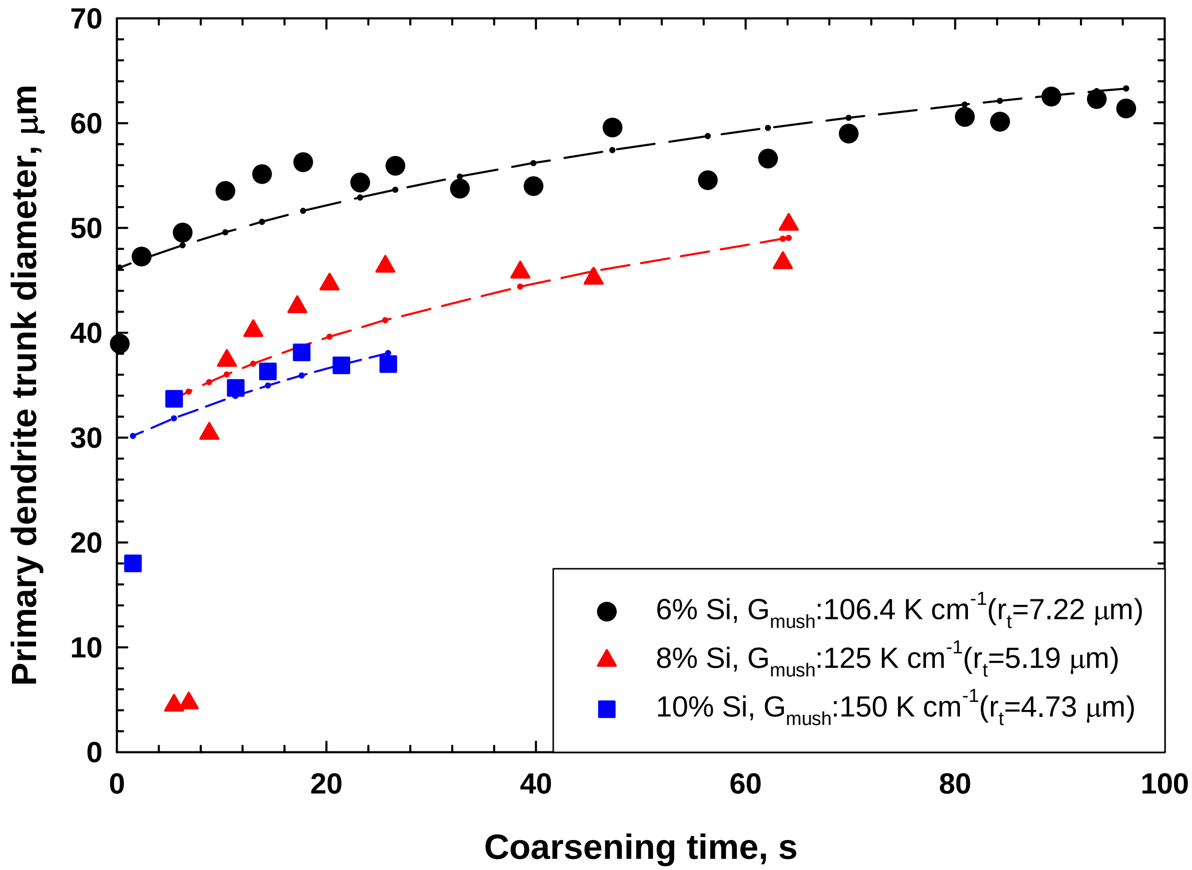


Trunk diameters in the mushy-zone are greater than those expected from the Trunk diameter model.

Trunk diameter measured in quenched mushy-zone

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

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

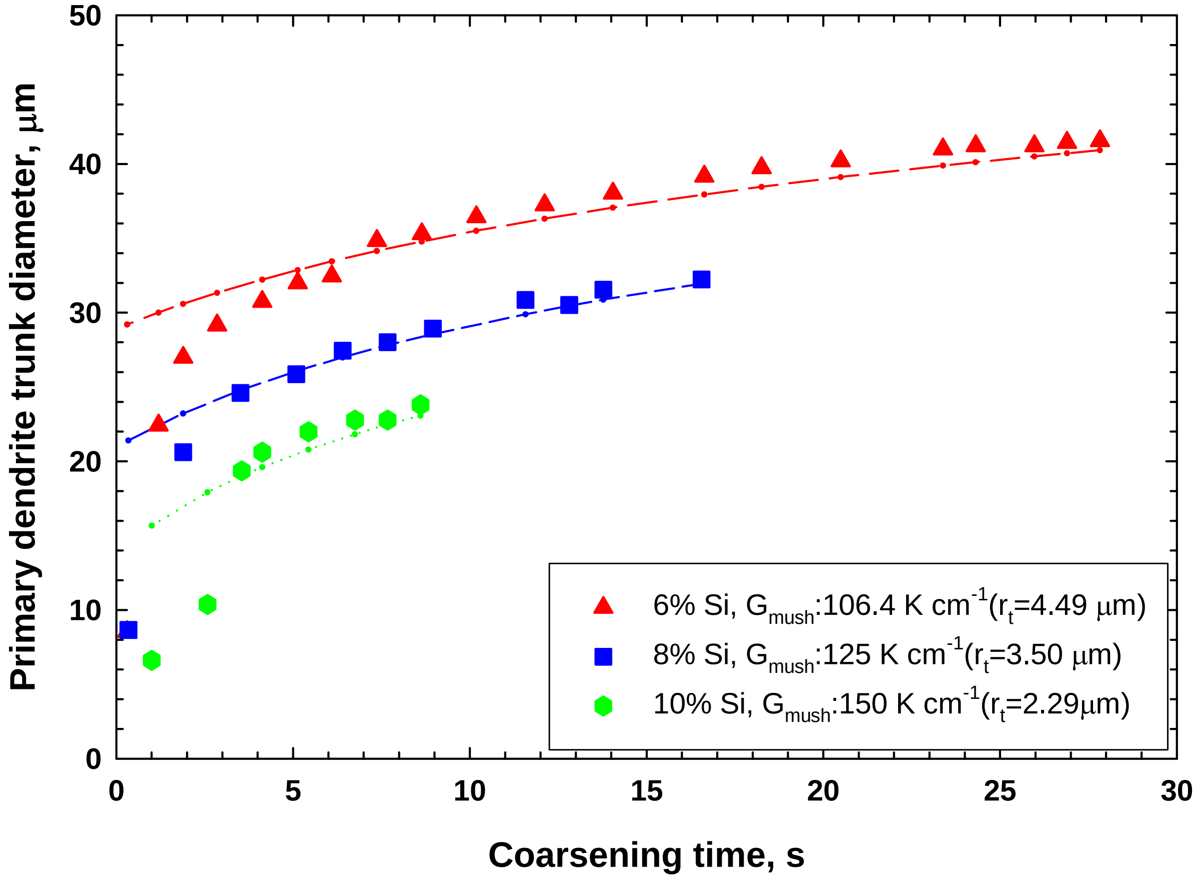


These r_t values are larger than predicted from Trivedi/or Hunt-Lu models.

Trunk diameter measured in quenched mushy-zone

Al-Si alloys: Growth speed 156 μm s^{-1}

Lines: Vary $\mathbf{r_t}$ 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.

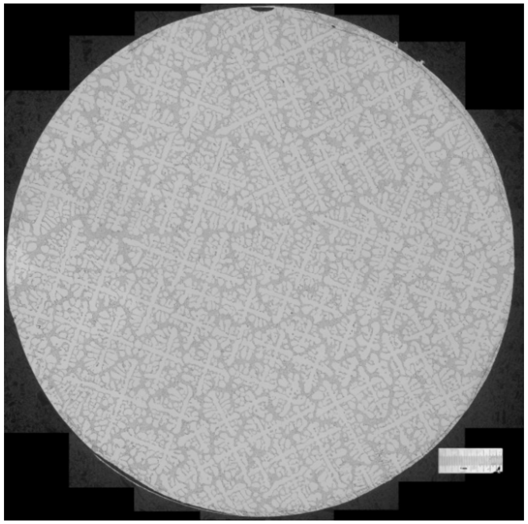
The tip radii obtained by forcing a least squared fit of the observed trunk diameter vs. time data to the trunk-diameter coarsening equation are larger than the tip radii calculated from the Hunt-Lu or Trivedi models.

C_o wt%	G_l K/cm	G_m K/cm	R μm/s	r_t_HL μm	r_t_Trivedi μm	r_t from best fit least squared analysis μm
6	150	106.4	43	4.28	5.48	7.22
8	150	125	43	3.41	4.35	5.19
10	150	150	43	3.06	3.9	4.73
6	150	106.4	156	2.21	2.75	4.49
8	150	125	156	1.76	2.21	3.5
10	150	150	156	1.58	1.99	2.29

Does natural convection during terrestrial directional solidification increase dendrite trunk diameter (dendrite tip radius?)

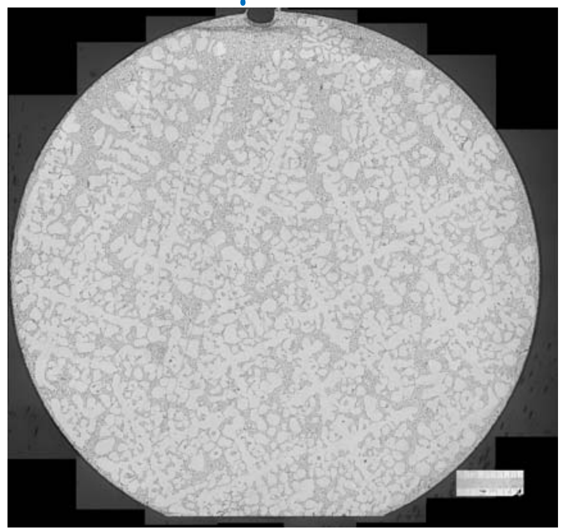
Comparison of microstructures: Al-7% Si directionally solidified on ground and on ISS (MICAST6)

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

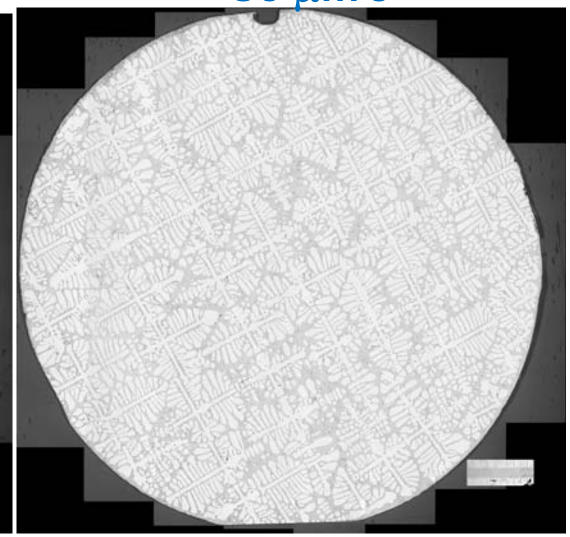


MICAST6: 20 K cm^{-1}

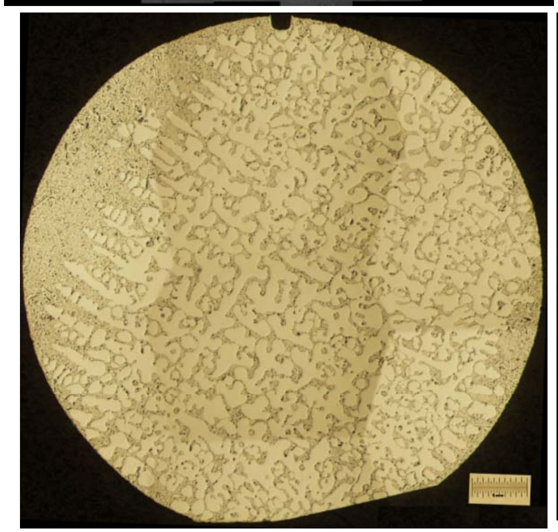
5 $\mu m\ s^{-1}$



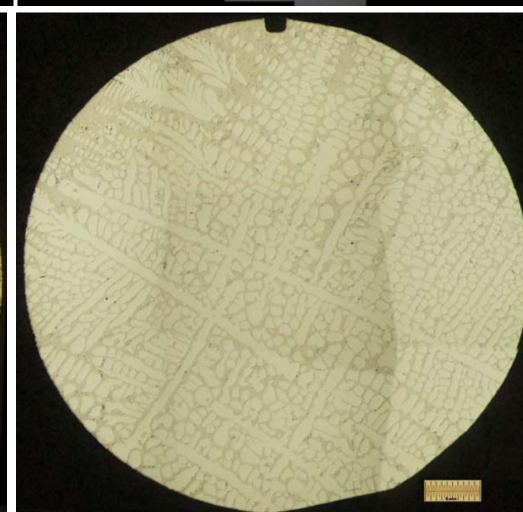
50 $\mu m\ s^{-1}$



Terrestrial DS:
15 K cm^{-1} ➔



5 $\mu m\ s^{-1}$

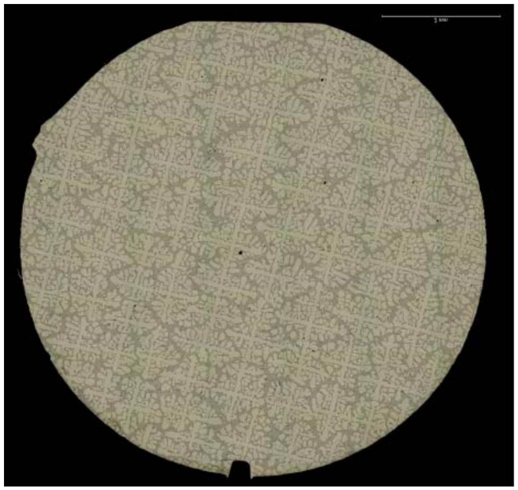


50 $\mu m\ s^{-1}$

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

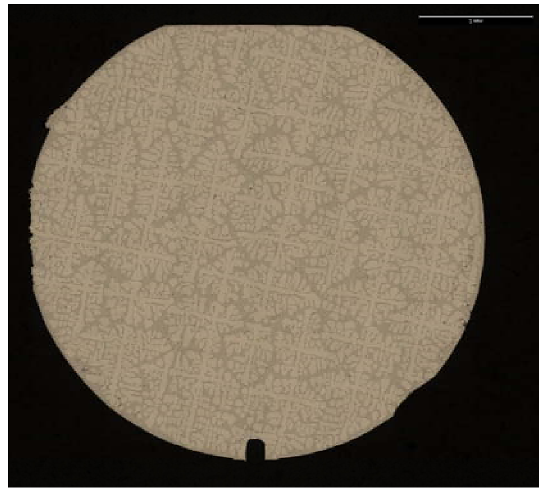
Comparison of microstructures: Al-7% Si directionally solidified on ground and on ISS (MICAST7)

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

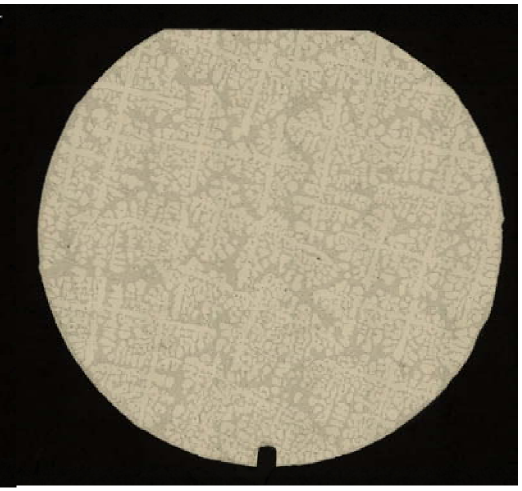


MICAST7: 26 K cm^{-1}

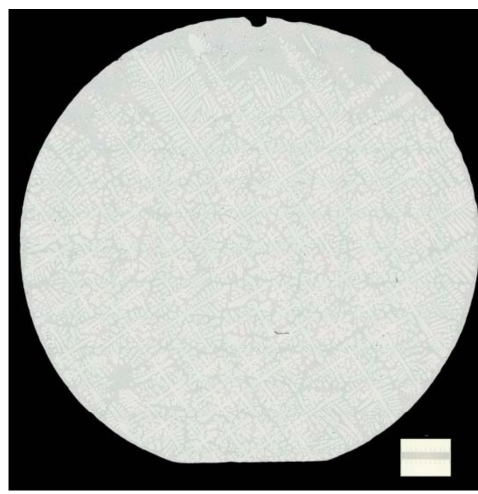
21 μm s^{-1}



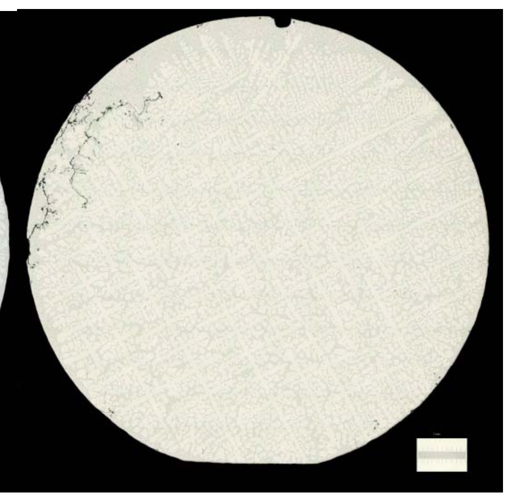
11 μm s^{-1}



Terrestrial DS:
24 K cm^{-1} ➔

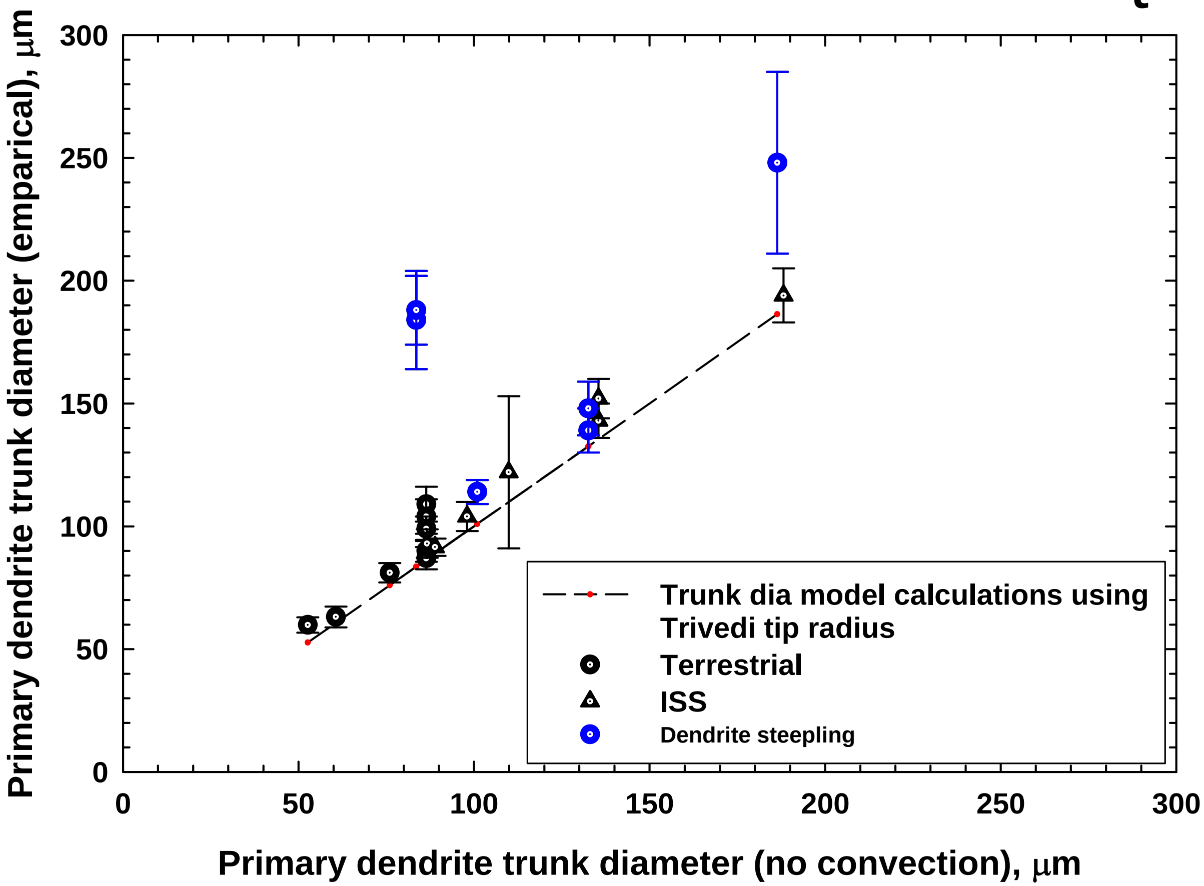


23 μm s^{-1}



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 <u>increases</u> trunk diameter.**

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

	Trivedi		
	ISS-samples	**Terrestrial (no steepling)**	**Terrestrial (steepling)**
Primary dendrite arm spacing/calculated from model	0.945± 0.0833	0.791± 0.0931	0.695± 0.223
Primary dendrite trunk diameter/calculated from model	**1.069± 0.0361**	**1.113± 0.0890**	**1.513± 0.560**

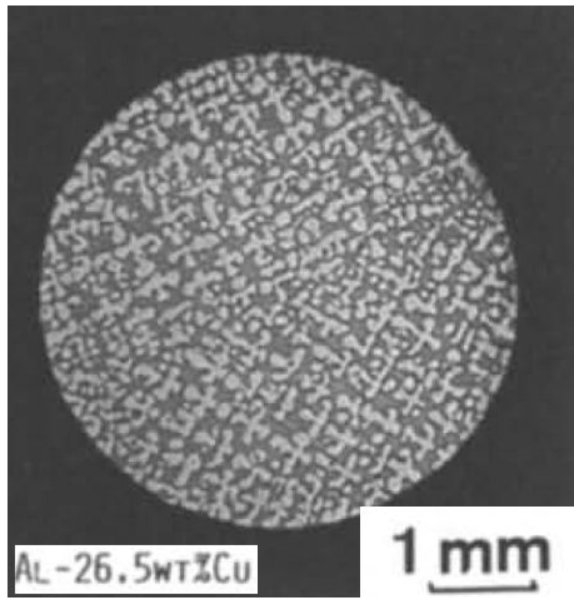
Natural convection decreases primary dendrite arm spacing and increases primary dendrite trunk diameter in Al-26.5 % Cu

(M.D. Dupouy, D. Camel and J.J. Favier, Acta. Metall. Mater. Vol. 37, No. 4, pp. 1143-1157, 1989)

Al-26.5 wt% Cu, 30 K cm^{-1}, 4.2 $\mu m\ s^{-1}$

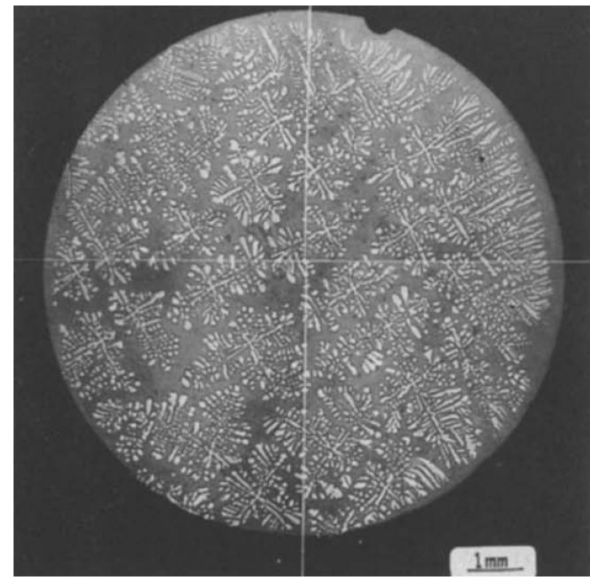
Terrestrial: Solutally stable, thermally stable mode

Al-26.5 wt% Cu, 25 K cm^{-1}, 4.2 $\mu m\ s^{-1}$



Terrestrial: Solutally unstable, thermally stable mode

Al-26.5 wt % Cu, 30 K cm^{-1}, 4.2 $\mu m\ s^{-1}$



Microgravity:

	Terrestrial: Solutally stable, thermally stable mode	Terrestrial: Solutally unstable, thermally stable mode	Microgravity
Primary spacing ➔ $\sqrt{A/(N-1)}$	**450 ± 20 μm**	**34 0 ± 10 μm**	**1540 ± 10 μm**
Trunk diameter ➔	**120 ± 18 μm**	**122 ± 18 μm**	**92 ± 11 μm**

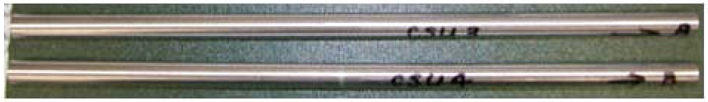
Conclusions

- 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.

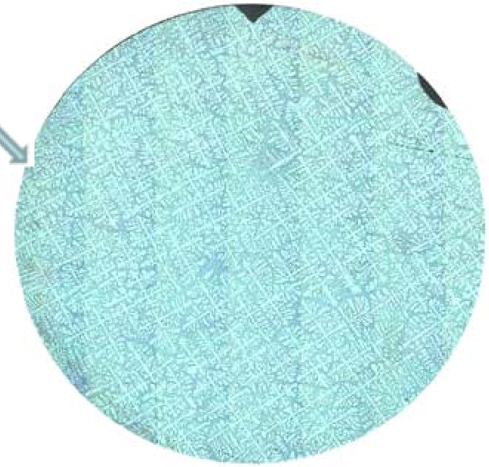
Acknowledgments

- NASA
- ESA
- Menn Glenn Chu (ALCOA)
- 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.



(Al-7%Si Single Crystal Dendritic)



Transverse View

ESA- Sample Cartridge Assembly

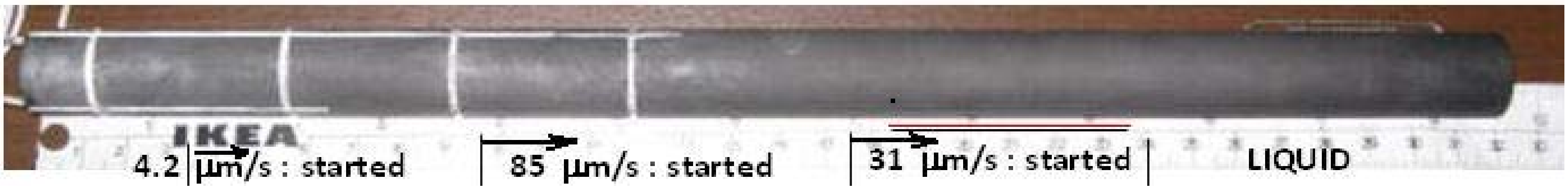
ESA_MSL Low Gradient Furnace

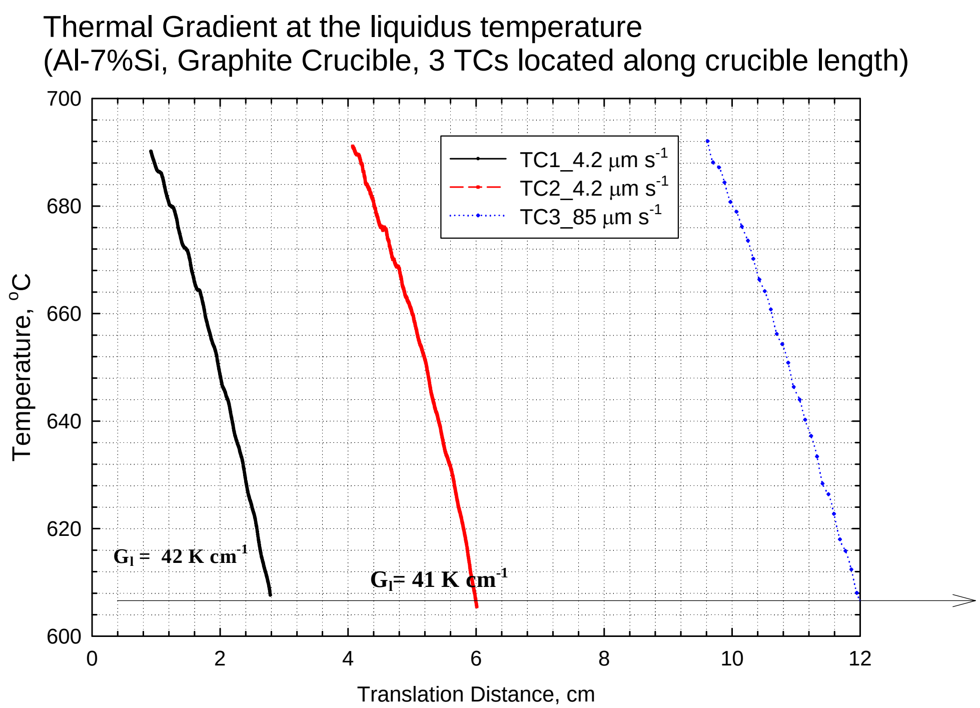
ESA:
Material
Science
Laboratory

NASA_MSSR-1 Flight Rack

Terrestrial processing

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

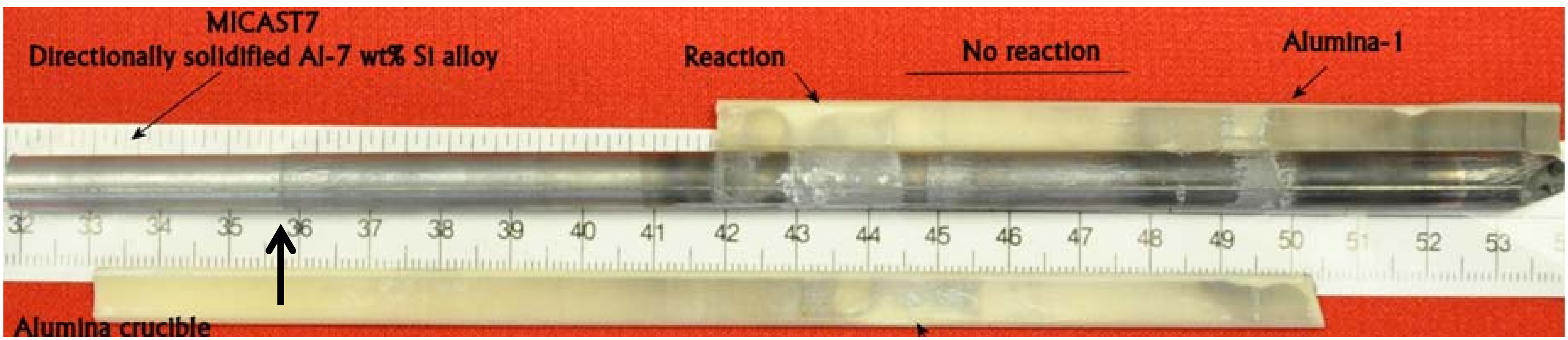




Microgravity Processed Sample MICAST 7

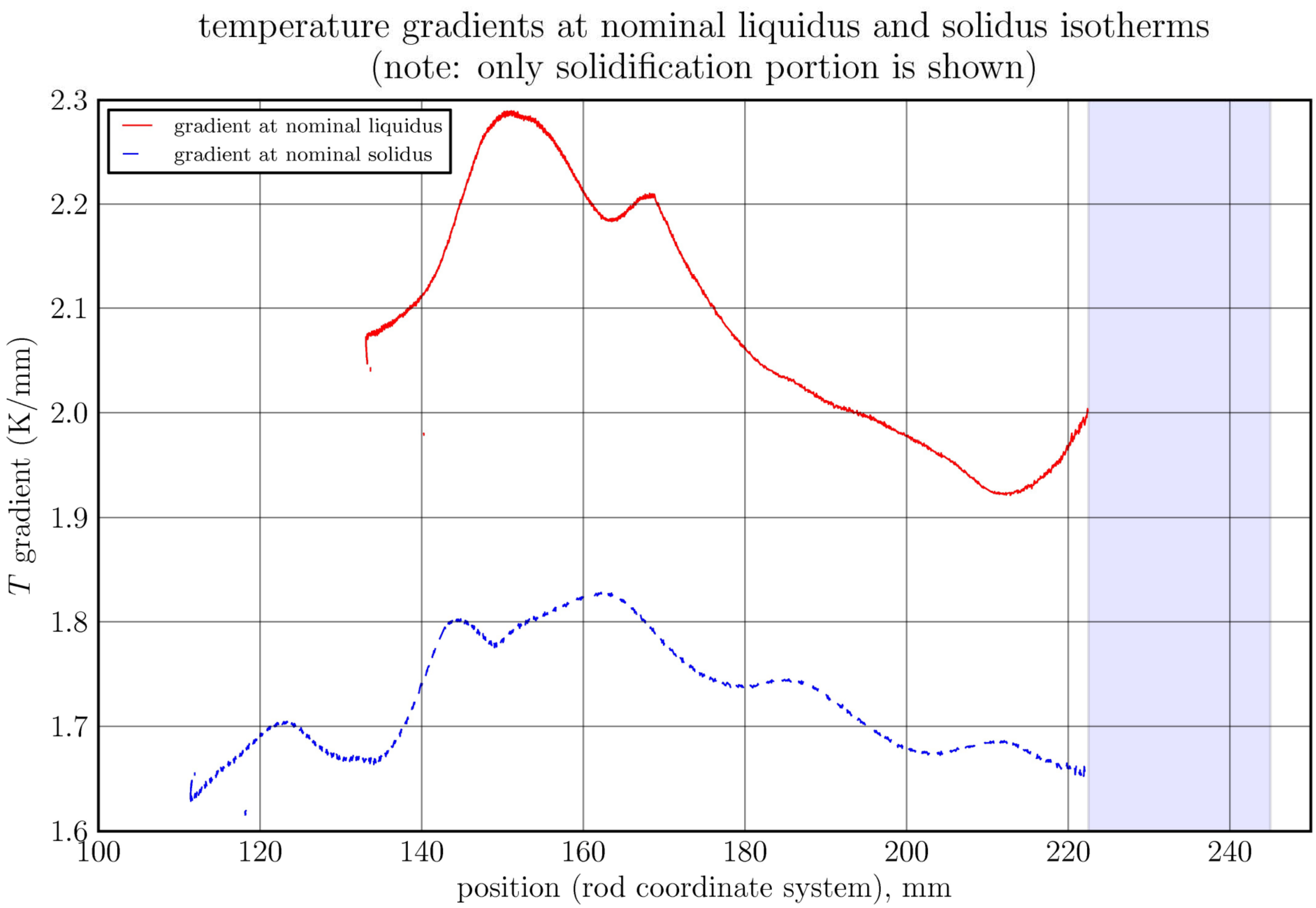
Eutectic Melt Back / Isotherm

X-ray radiograph of MICAST7

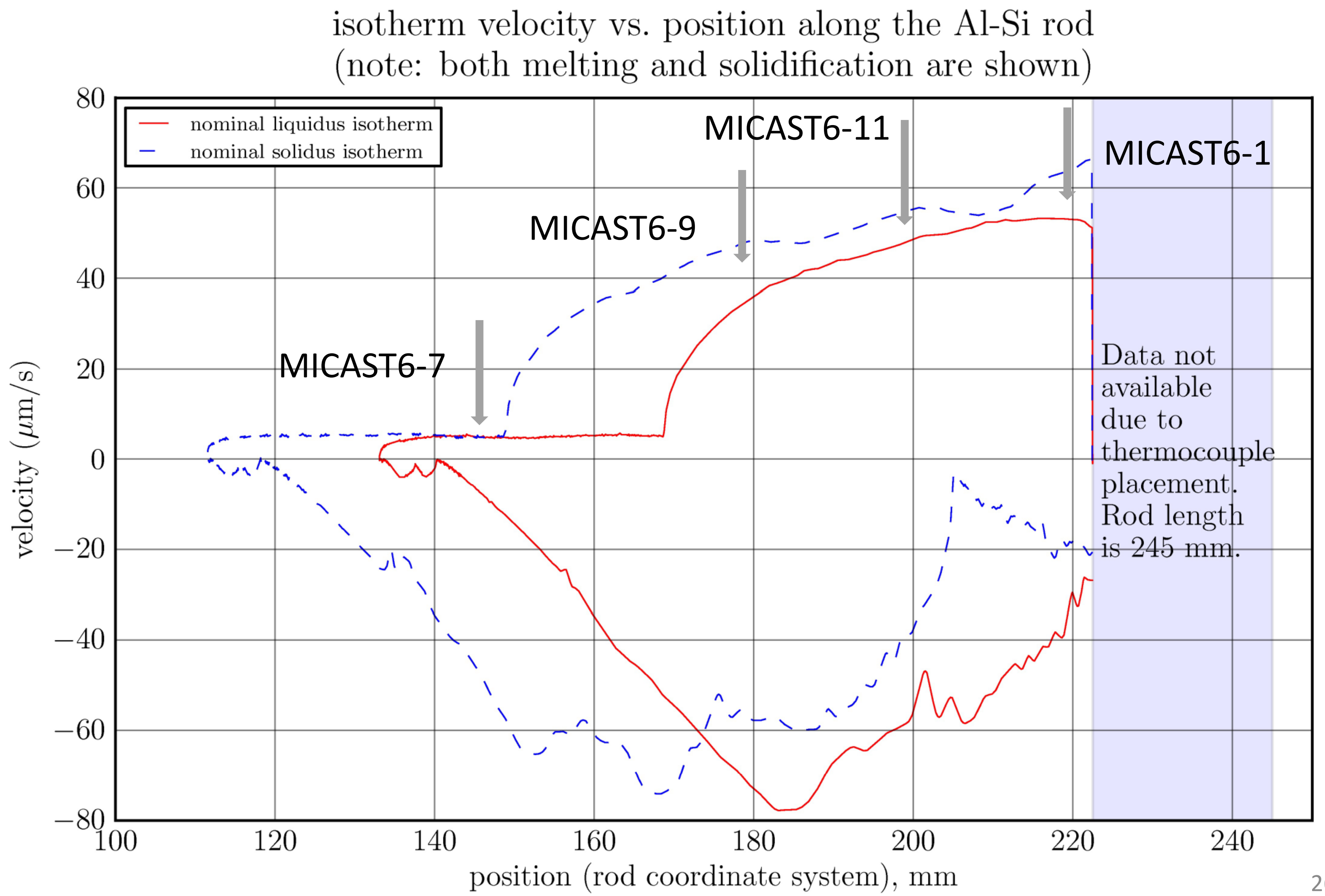


Eutectic Melt Back

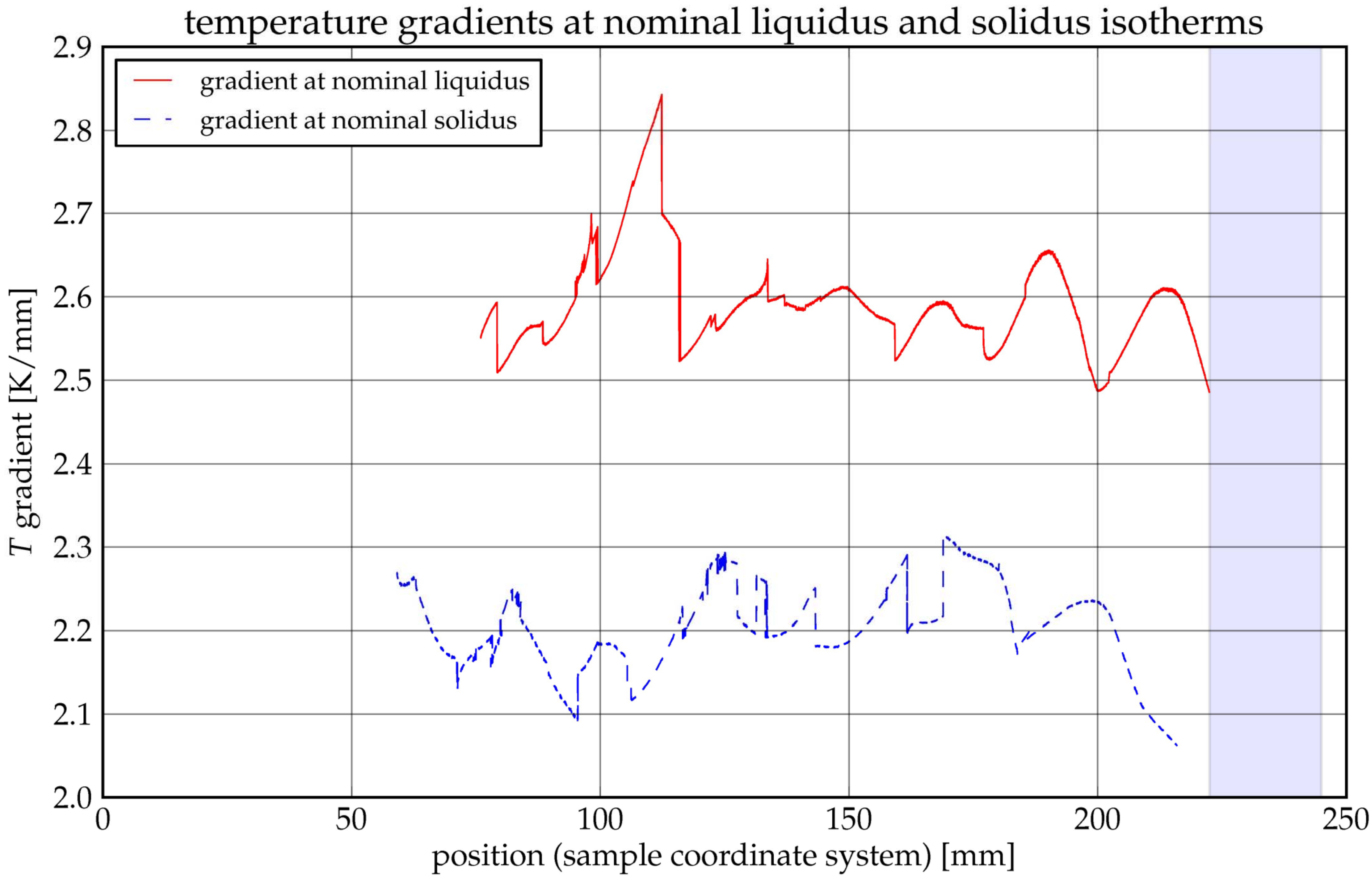
MICAST6: ESA-Low Gradient Furnace (1-hr heat-up, 5-hr hold, G_l~ 20 K cm^{-1}): 3.8 cm at 5 μm s^{-1}, 11.3 cm at 50 μm s^{-1}



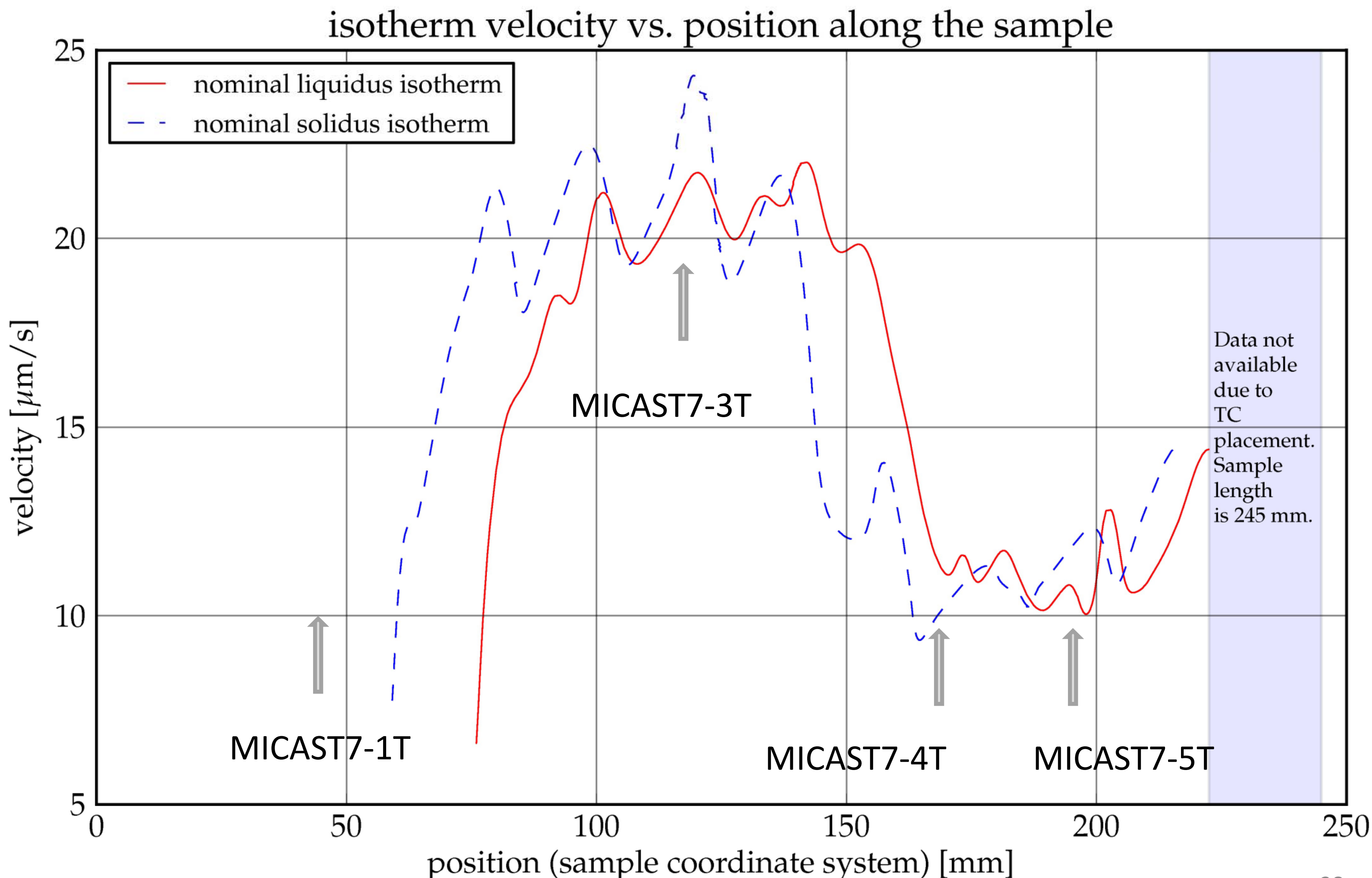
MICAST6: ESA-Low Gradient Furnace (1-hr heat-up, 5-hr hold, G_l~ 20 K cm^{-1}): 3.8 cm at 5 $\mu m\ s^{-1}$, 11.3 cm at 50 $\mu m\ s^{-1}$



MICAST7: ESA-SQF (1-hr heat-up, 1-hr hold (G_l ~ 26 K cm^{-1}): 8.4 cm at 20 $\mu m\ s^{-1}$, 6.5 cm at 11 $\mu m\ s^{-1}$



MICAST7: ESA-SQF (1-hr heat-up, 1-hr hold (G_l ~ 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

Sample ID	G_l, K cm^{-1}	G_m, K cm^{-1}	R, µm s^{-1}
MICAST6-1	19	18	52
MICAST6-11	20	18.5	47
MICAST6-9	21	19.3	34
MICAST6-7	22.8	20.4	5
MICAST7-3T	26	24	20
MICAST7-4T	26	24	11
MICAST7-5T	26	24	11