In-situ studies of dendrite fragmentation in Al-Cu.

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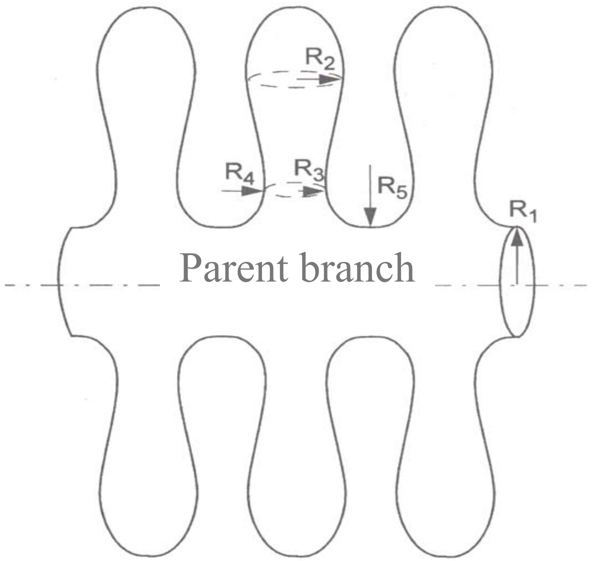
Dendrite detachment



- Detachment by local remelting

$$\frac{d(\Delta T)}{dt} < 0 \qquad \Delta T = \Delta T_t + \Delta T_c + \Delta T_r$$

- Initiated/driven by:
  - solute pileup in the mush (e.g. from transient growth/liq.flow)

$$\frac{d}{dt} \nabla C \,\Big|_{\text{int}} < 0$$

  - recalesence

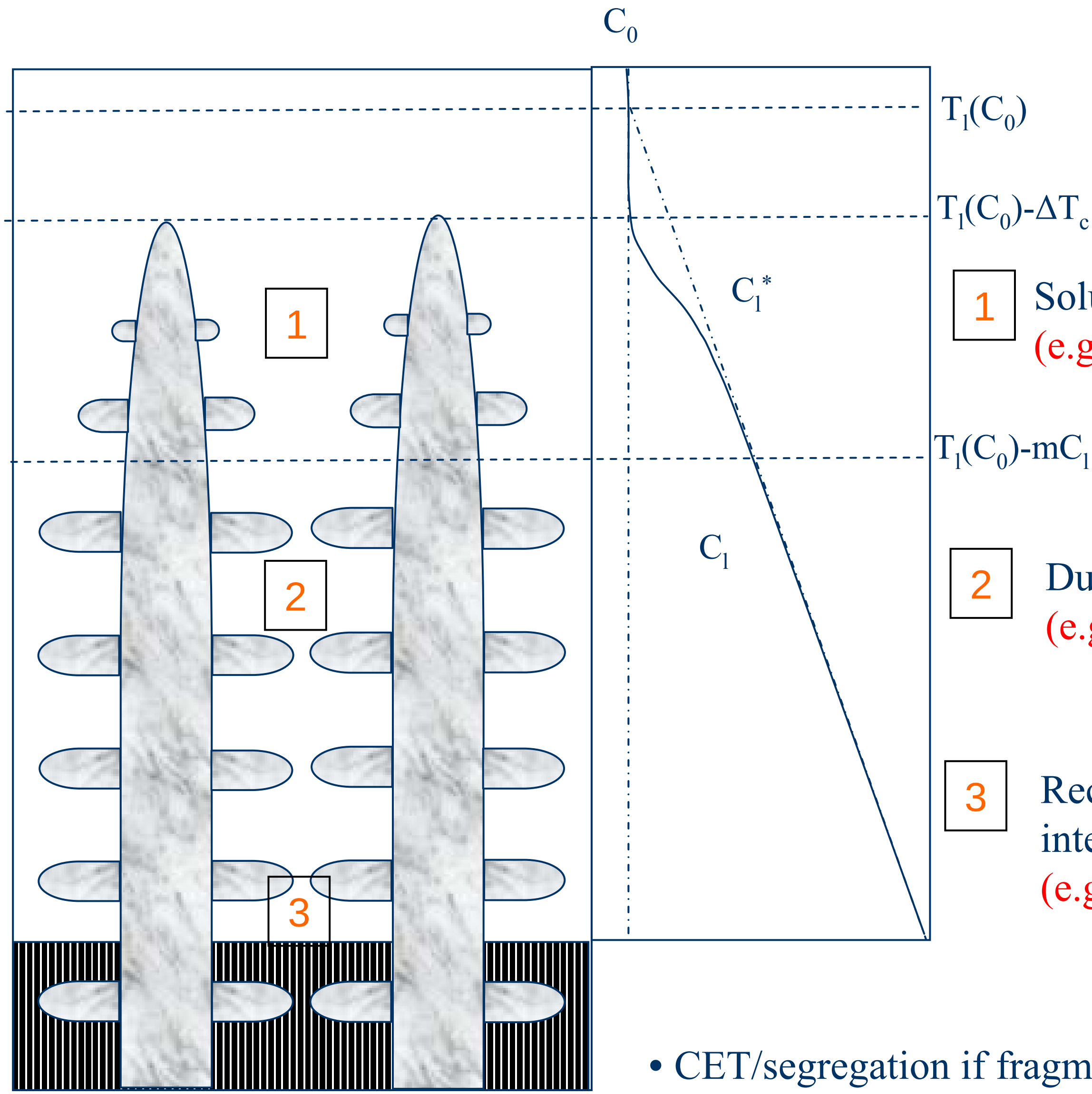
$$\Delta h_f \frac{df_s}{dt} > q_e \frac{A}{v}$$

+ curvature contribution towards final necking

- Local mush curvatures/undercoolings in delicate balance

- Detcachment if: $R_2 \dfrac{dR_3}{dt} < R_3 \dfrac{dR_2}{dt}$

Dendrite detachment – where/when ?



1 Solute pile-up in the undercooled region
(e.g. Mullis *et al*, Liu *et al*, Yasuda *et al)*

2 During coarsening
(e.g. Jackson *et al*, Li *et al*)

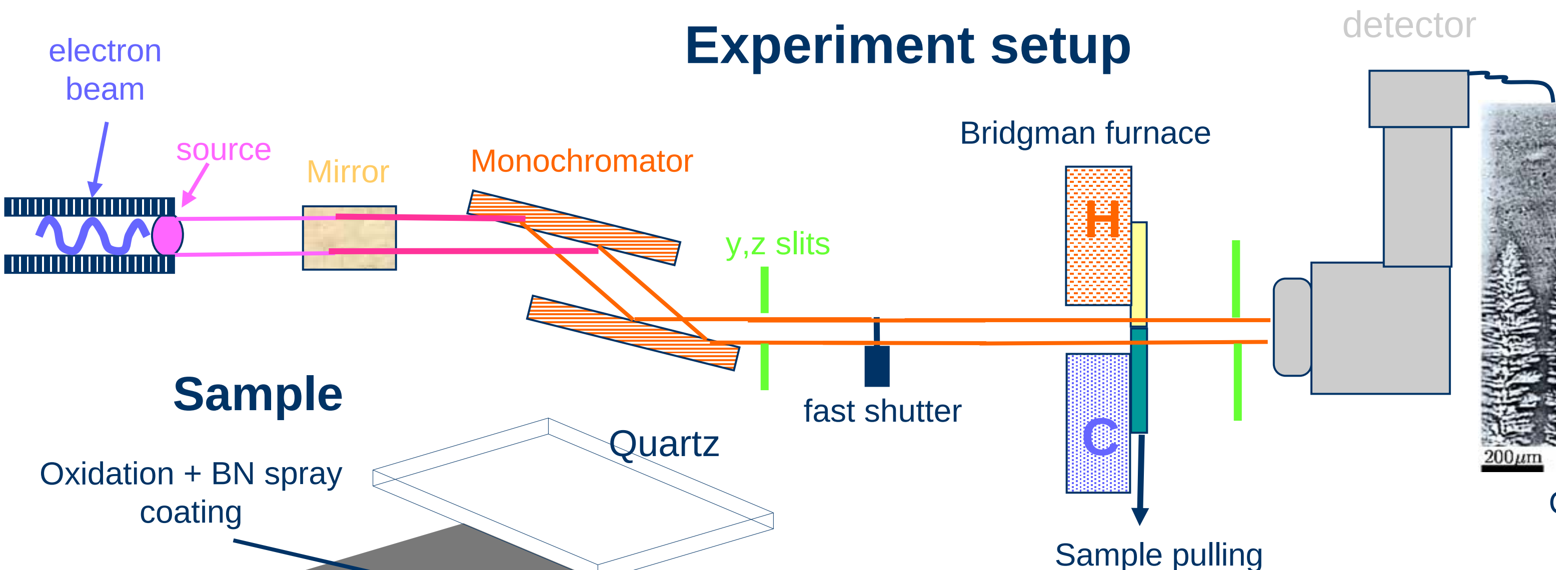
3 Recalesence from solidification of the interdendritic liquid
(e.g. Herlach *et al*, Karma)

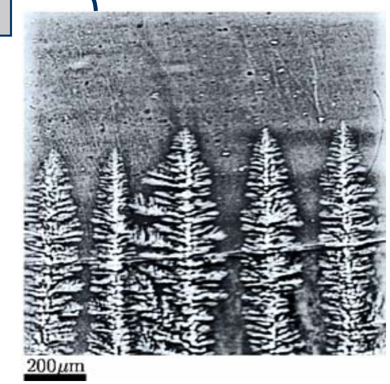
- CET/segregation if fragments are transported to the columnar front

Experiments

- Fragmentation during DS in Al-20%wtCu and Al-30%wtCu
- DS parallel and anti parallel with **g**

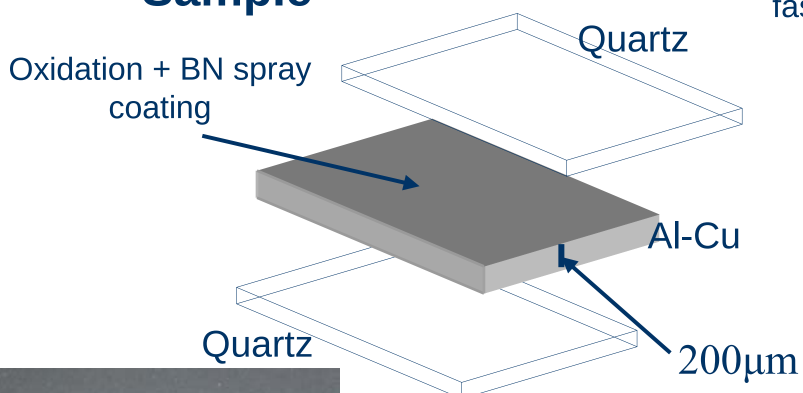
Experiment setup





Computer screen

Sample



- E= 12-15 keV, $\Delta E/E \sim 10^{-4}$
- Flux at sample: ~5x10^{12} ph/(s•mm^{2}) (~ 10^{6}-10^{10} conventional sources)
- Nominal resolutions:
  - $\Delta r \sim 1.4$ µm
  - $\Delta t \sim 0.15$ s
- Contrast from attenuation *and* refraction

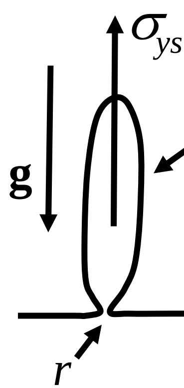
- <u>Convection </u>(Beckermann):

$$Ra_c = \frac{\Delta\rho}{\rho_0}\frac{gF(\overline{f_s})\lambda_1 l_z t_x}{vD_l}$$

$$\Rightarrow Ra_{20wtCu} \sim 1 \times 10^6\ \text{m/K G}^{-1} (< 100), \qquad Ra_{30wtCu} \sim 2 \times 10^7\ \text{m/K G}^{-1} (< 1800)$$

- <u>Bouyancy on the solid network</u>:

$$F_g(t) = \Delta\rho(t)V(t)g - F_d(t),$$



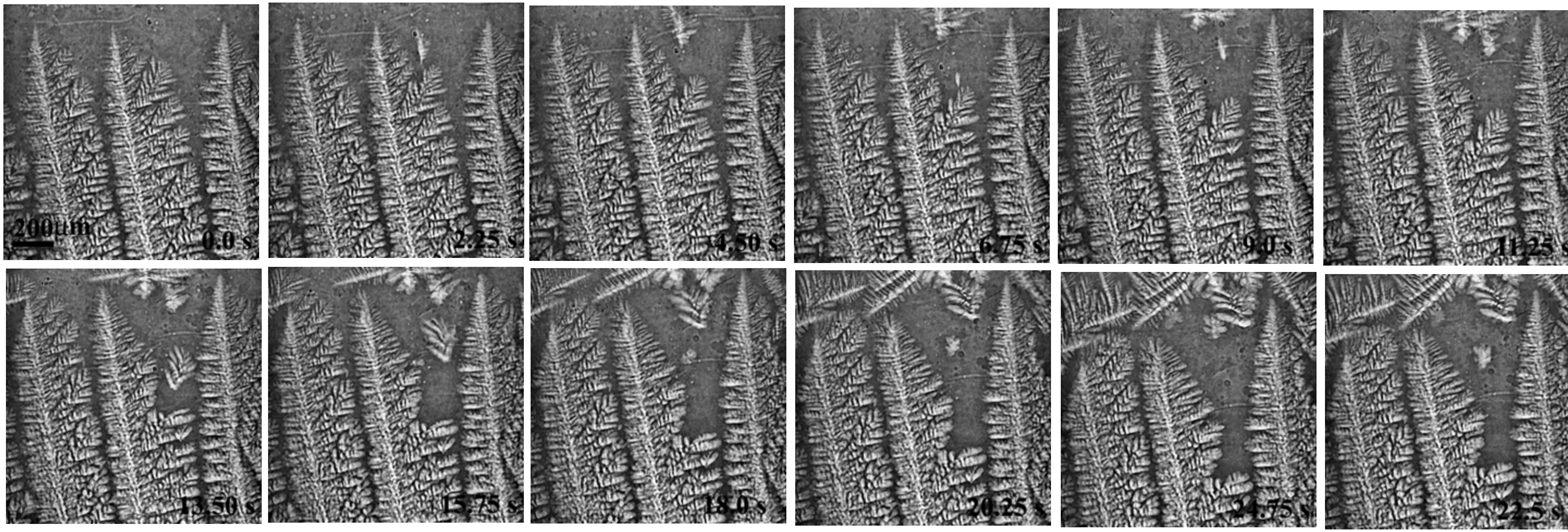
$$V = V_e = \frac{4}{3}\pi R_e^3,$$

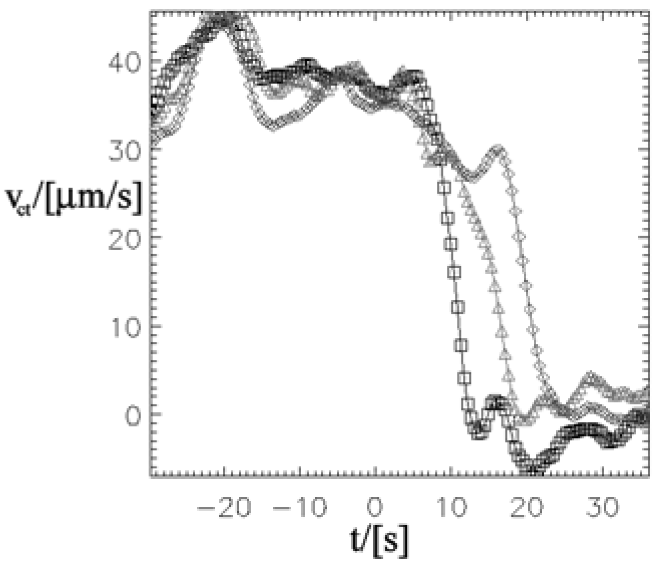
Contributes to final necking if: $R_e > \left(\frac{3\sigma_{ys}}{4\Delta\rho g} r^2\right)^{1/3}, \qquad \sigma_{ys} \geq 10\ \text{MPa}$

$$\Rightarrow R_e \geq 300\ \mu\text{m}$$

Results

1 Solute pileup





Columnar tip velocities

$G = 48$ K/mm, $v_{sp} = 25$ µm/s

Ra ~ 20

20%wtCu

Results

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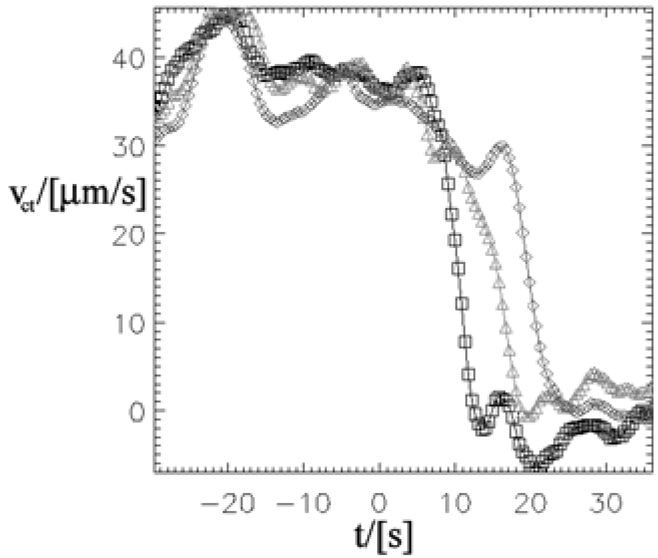


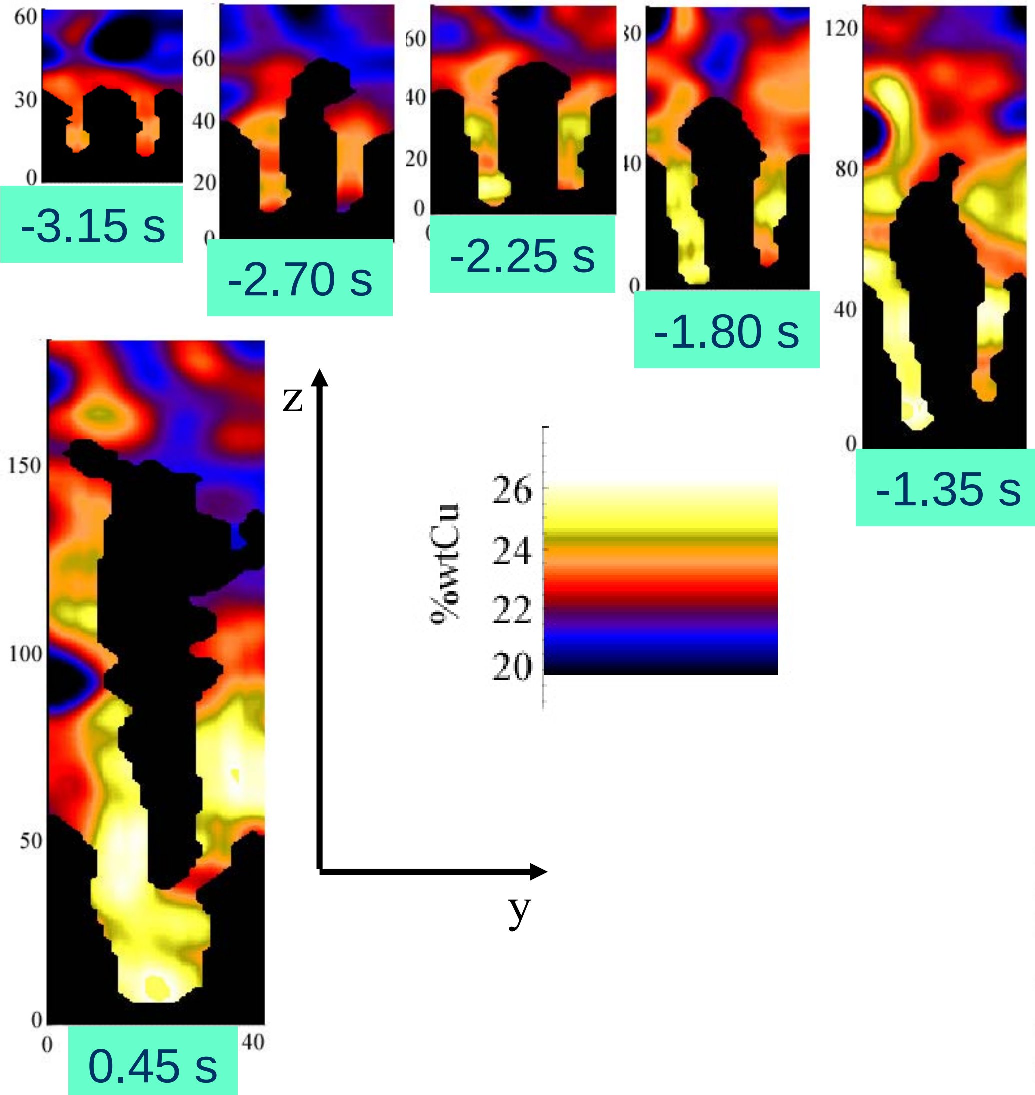
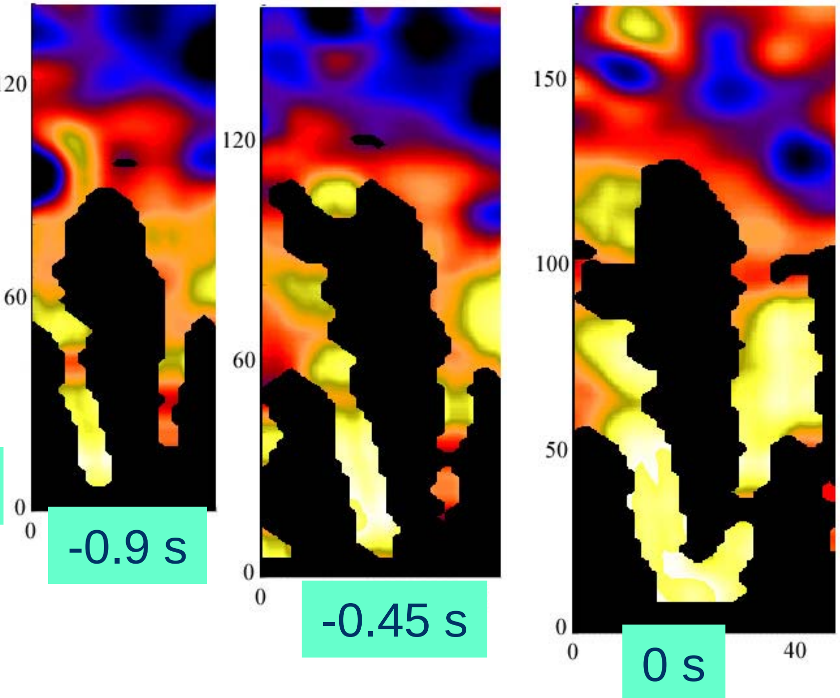
Columnar tip velocities

1.21 mm

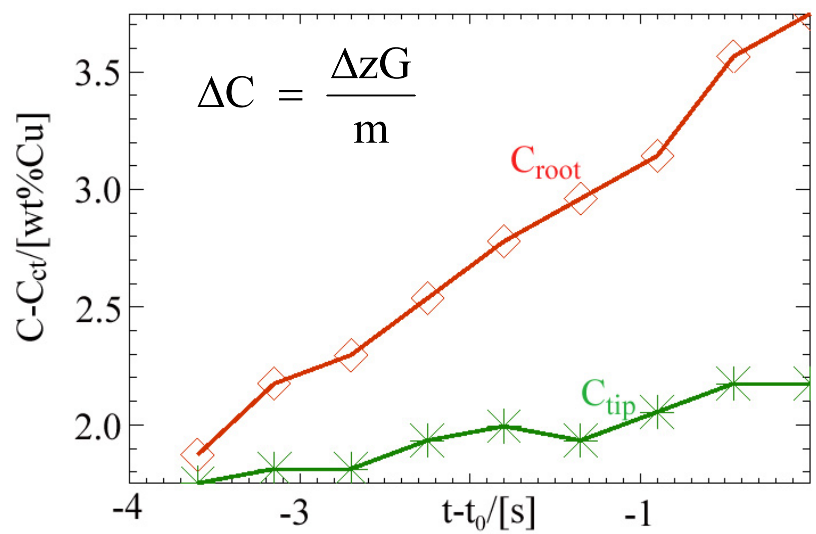
G = 48 K/mm, v_{sp} = 25 µm/s

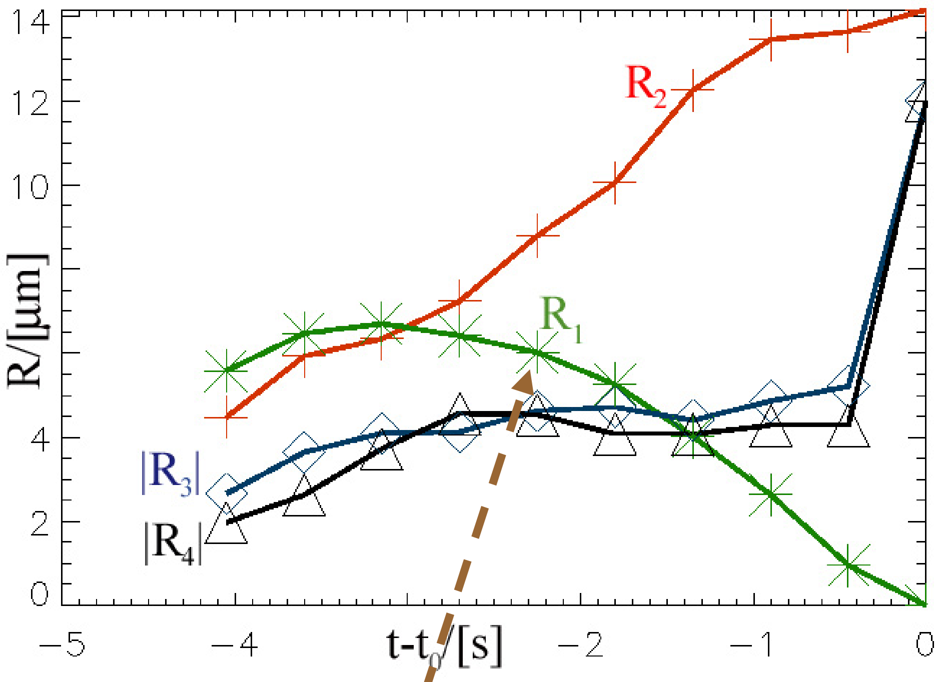
Ra ~ 20

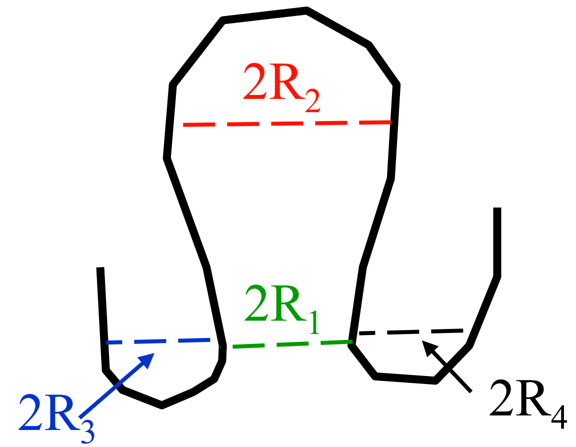
20%wtCu

$$\overline{(v_{tip} - v_{ct})} \sim 2\,\mu m/s$$



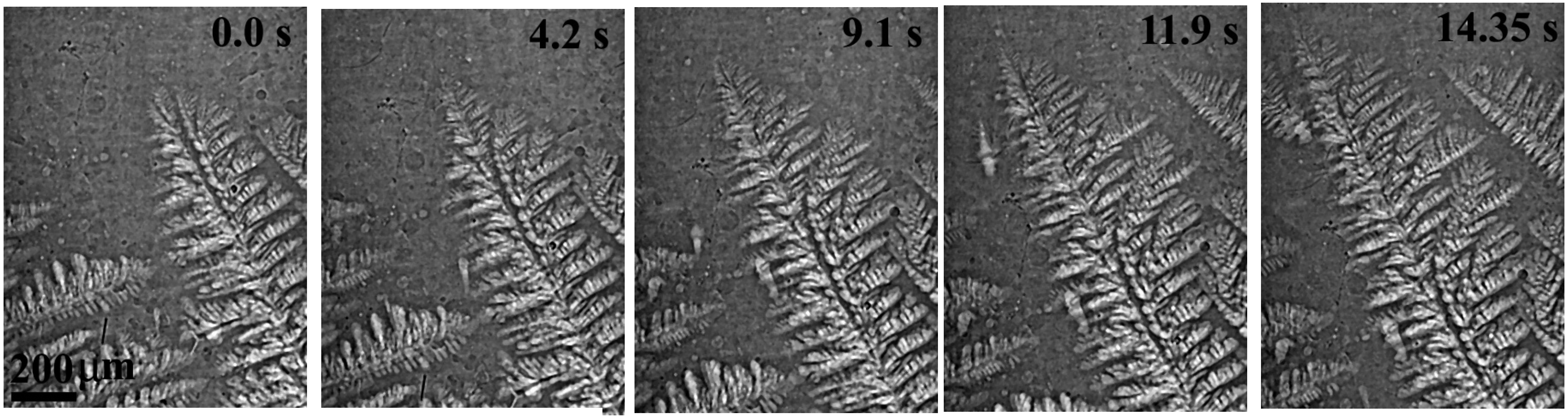


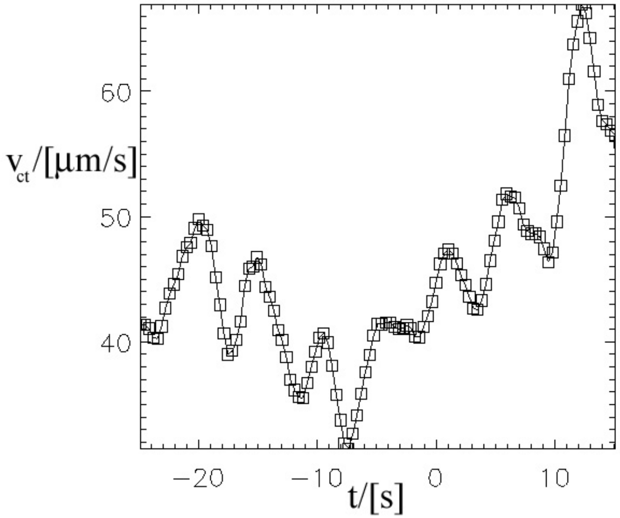


$$\left.\frac{\partial C}{\partial y}\right|_{\text{int}} \sim 0$$

Results

2 Coarsening





Columnar tip velocity

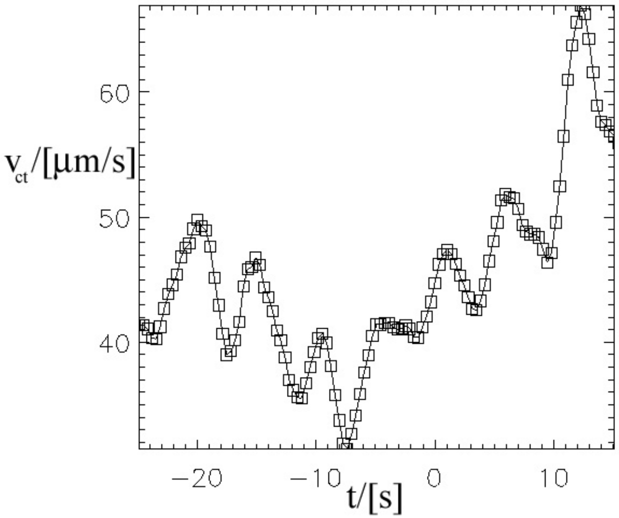
G = 13.5 K/mm, v_{sp} = 32.5 μm/s

Ra ~ 80

20%wtCu

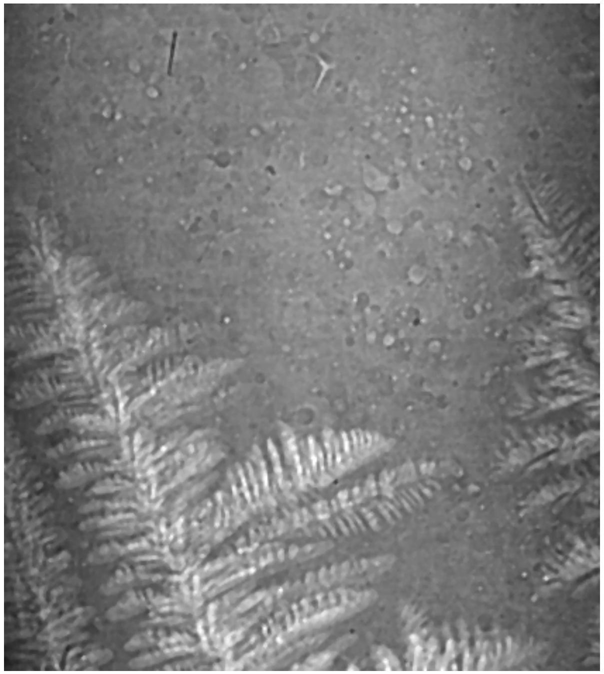
Results

2 Coarsening



Columnar tip velocity

0.8 mm



G = 13.5 K/mm, v_{sp} = 32.5 μm/s

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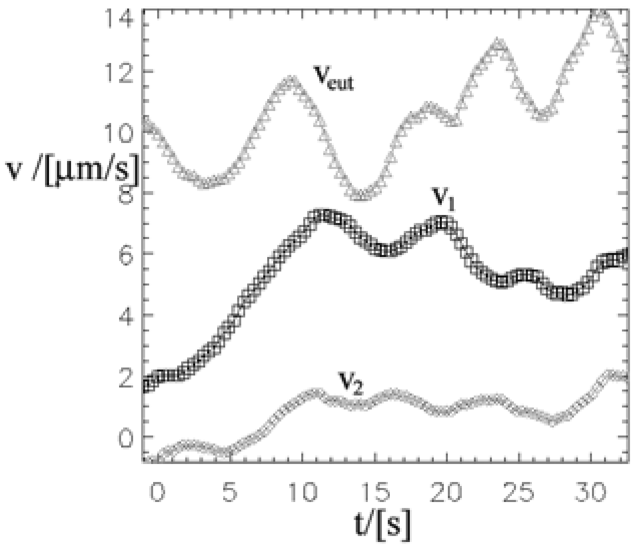
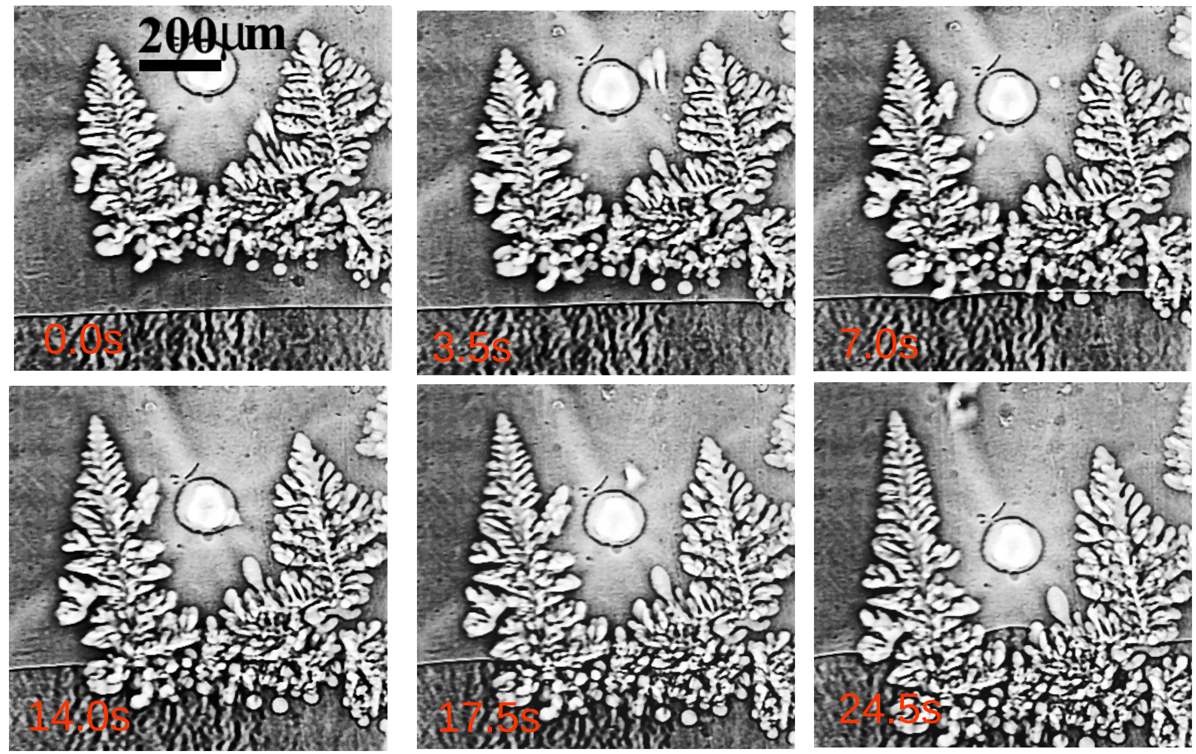
20%wtCu

Results

3 Recalescence





$$f_e = f_l(T_{eut}) \approx 0.83$$

$$\overline{V_{eut}} \sim 2V_{sp}$$

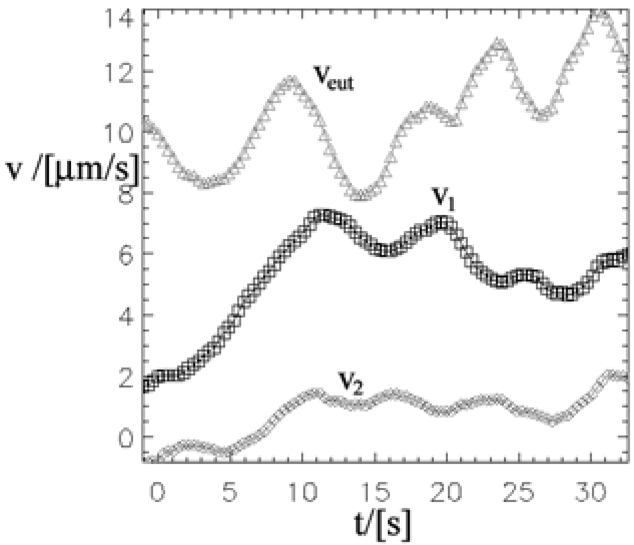
G = 15.8 K/mm, v_{sp} = 5 μm/s

Ra ~ 1200

30%wtCu

Results

3 Recalescence



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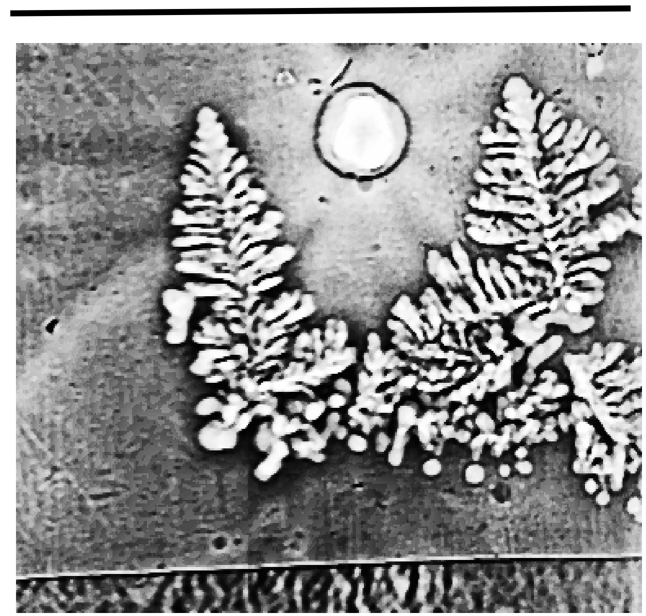
0.8 mm



G = 15.8 K/mm, v_{sp} = 5 µm/s

Ra ~ 1200

30%wtCu

1 Solute pileup - up front

1.21 mm

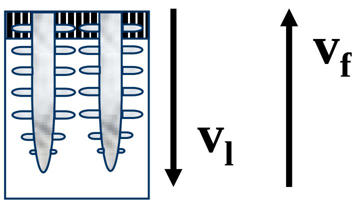
G = 48 K/mm, v_{sp} = 25 μm/s

Ra ~ 20

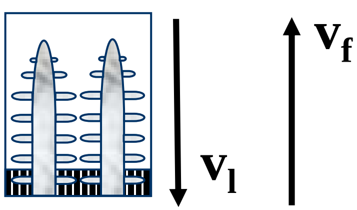
20%wtCu

Summary of the experiment

Alloy	# fragm seq G || g	# fragm seq G || -g
Al-20%wtCu	0 (4)	20 (22)
Al-30%wtCu	0 (3)	8 (17)
Total	0 (7)	28 (39)



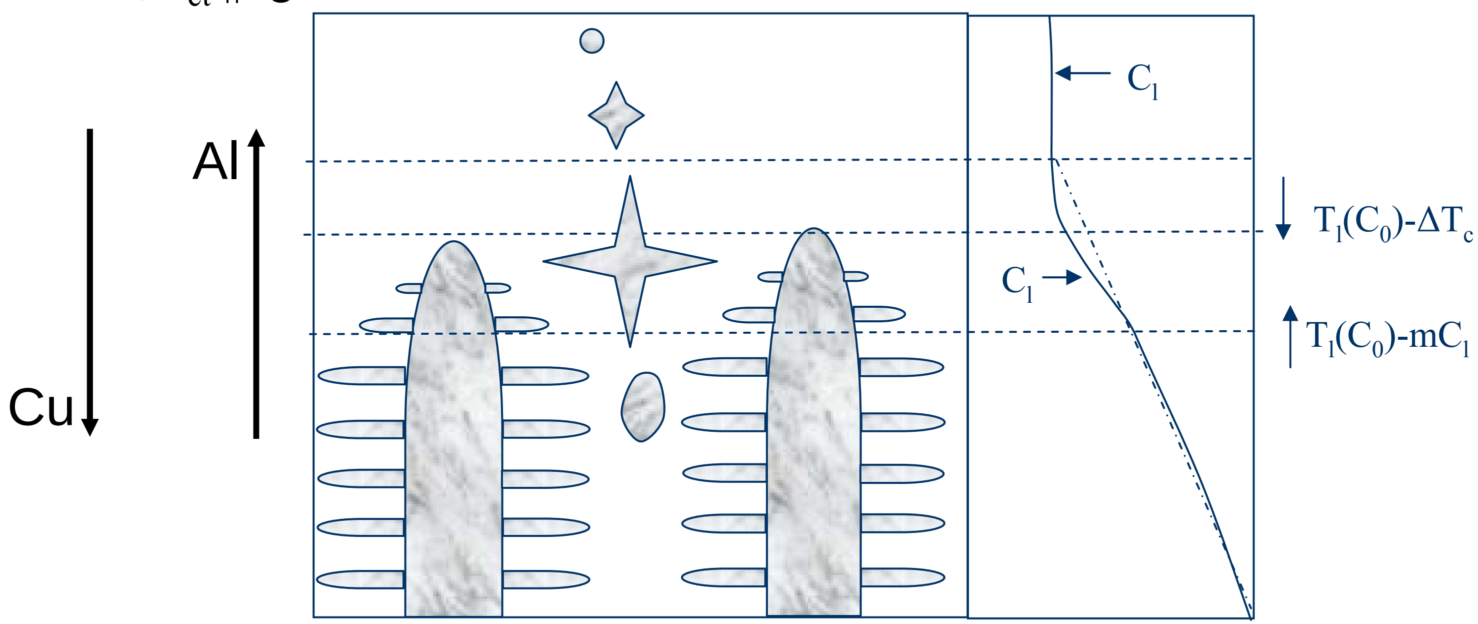
- ||**g**: Solute boundary destabilization (Diepers & Steinbach)
  Fragment transport deeper into the mush
  No CET



- || -**g**: Mush solute pileup with (dv_{tip}/dt).
  Copious fragmentation by depletion of the intercolumnar undercooling
  CET may initiate

- > %wtCu: More complete mush undercooling + eutectic,
  Less time for ripening,
  But more recalesence

In 3D, $v_{ct} \parallel -g$:



- Depletion of solvent in the mush and ahead of the columnar front
- Buoyant transport of Al to $T > T_l\ (C_0)$
- If fragmentation reinitiates: Alternating mesoscale segregation

Ackowledgements: Alcoa Automotive Castings, Scandinavian Casting Center ANS; Elkem Aluminium ANS; Fundo Wheels AS; Hydro Aluminium Metal Products; Hydro SA, Hydro Magnesium; the Netherlands Institute for Metals Research; Norwegian Research Council