Flow effects on the dendritic microstructure of AlSi-base alloys

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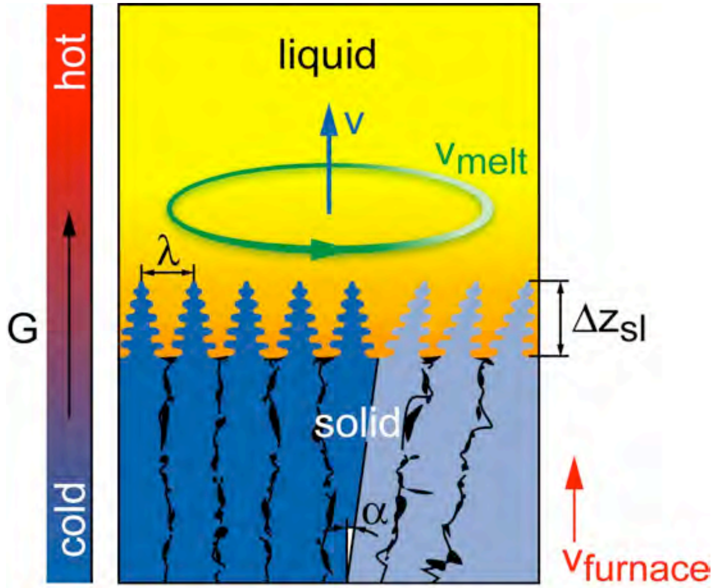
Flow effects on cast microstructures

Mass- and heat transport determine the solidified microstructure and its structural features:

- primary dendrite spacing
- secondary dendrite arm spacing
- eutectic spacing
- segregation
- specific surface area of the dendritic network
- fractal dimension of the branched dendrites
- precipitation of intermetallics
- ...

Effect of fluid flow on morphology is unkown in a quantitative sense !



Picture from G. Zimmerman ACCESS, Aachen

Therefore the ESA MAP* MICAST was established ten years ago to achieve

Quantitative understanding of the influence of fluid flow on the development and evolution of the microstructure of cast Al alloys.

→ **Development of global and microscopical models**
to predict the evolution of the microstructure under the influence of controlled fluid flow

→ **Experiments under microgravity conditions** (sounding rockets, ISS)
diffusive and controlled convective solidification conditions

→ **Laboratory experiments**
using **forced fluid flow by rotating magnetic fields**
as an experimental parameter

*MAP= Microgravity Application Project

Objectives of the present study

Microstructure evolution in

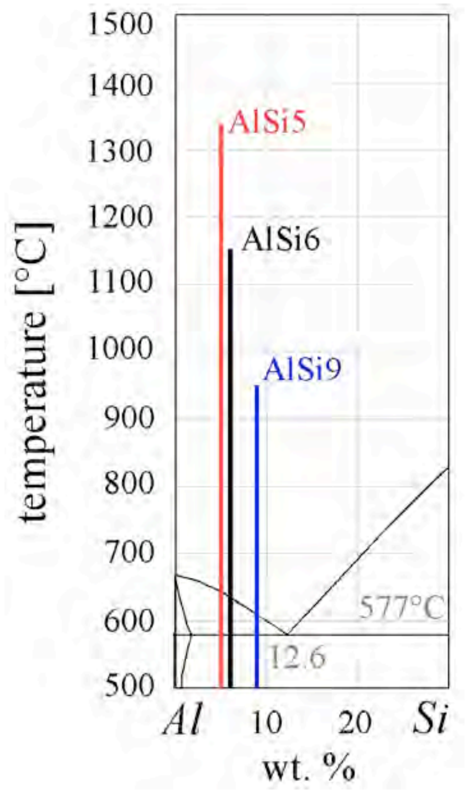
Some binary AlSi and two ternary AlSiCu alloys without fluid flow (laboratory and microgravity) and with fluid flow induced by RMF

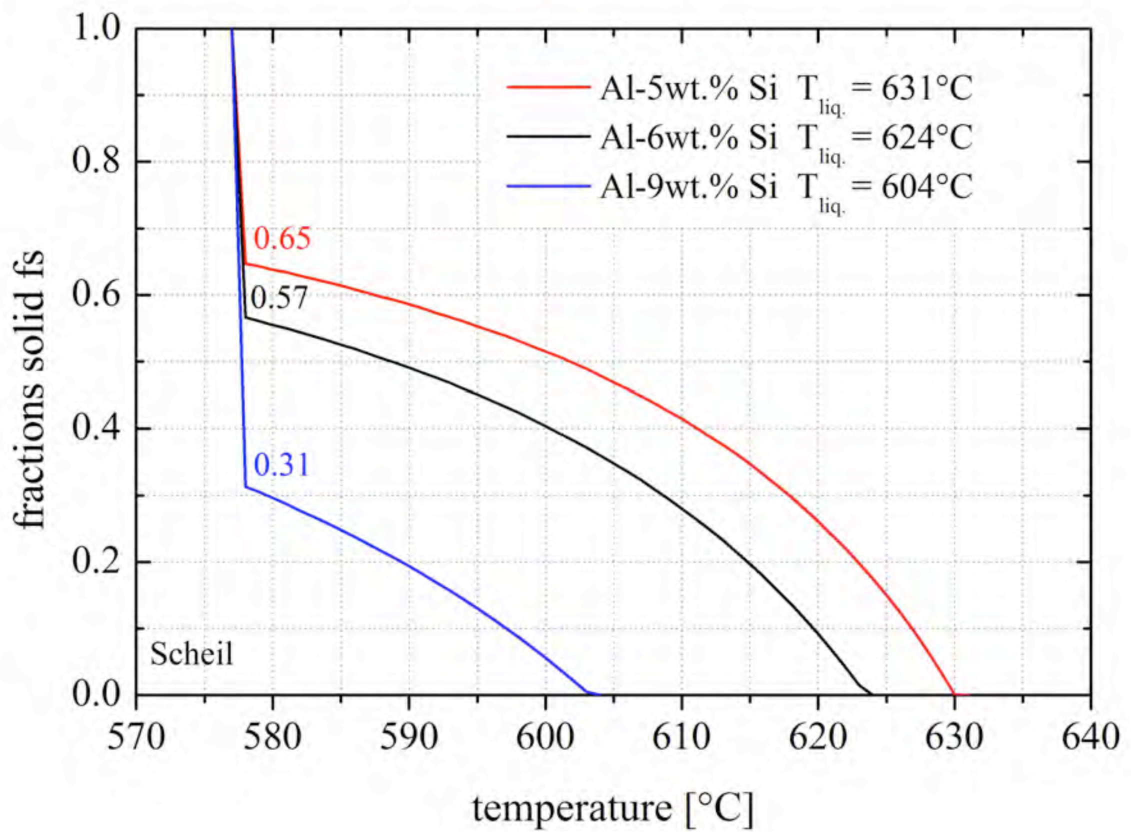
- Looking for good microstructural descriptors to catch the flow effects
  primary spacing, secondary spacing, specific surface area, fractal dimension

- Support (or not) of observations made on other alloys
  like AlSiCu, AlSiMg, AlSiFe, AlSiMn...

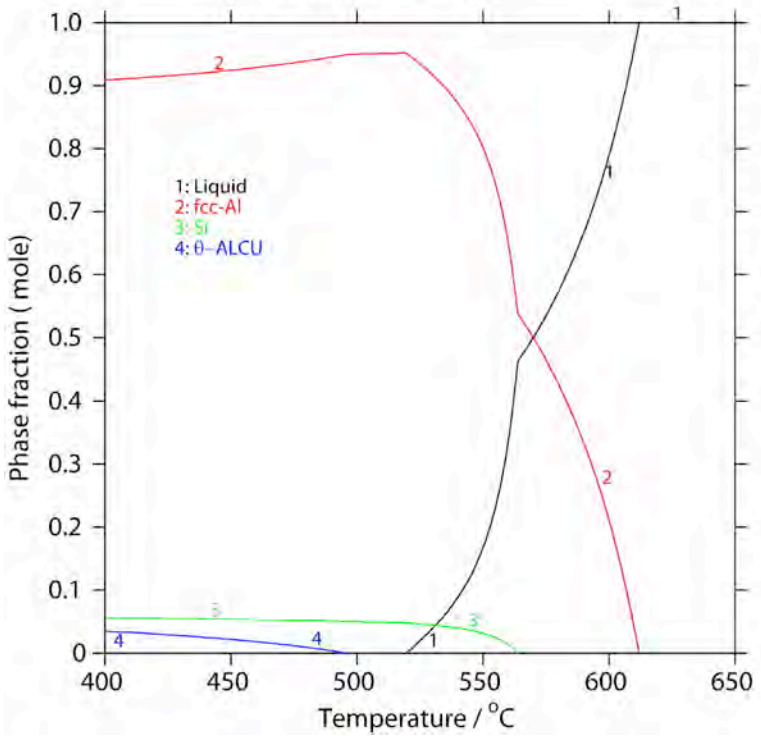
Experimental approach: the alloys

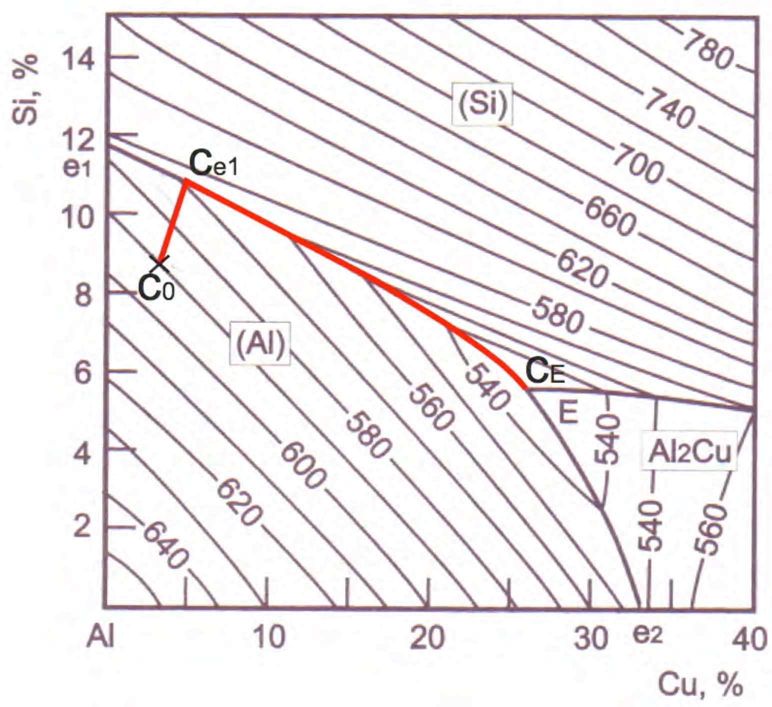
Al-5wt.%Si, Al-6wt.%Si, Al-9wt.%Si





AlSi6Cu4 and AlSi9Cu4 alloys





Al-6wt.%Si-4wt.%Cu
1: liquid
2: fcc-Al at 611.9 °C
3: Al-Si eutectic at 563.7 °C
4: Al-Si-Al_2Cu at 496.7 °
(after ThermoCalc, V.Witusiewicz)

Al-9wt.%Si-4wt.%Cu
1: liquid
2: fcc-Al at 590 °C
3: Al-Si eutectic at 569 °C
4: Al-Si-Al_2Cu at 523 ° C
(after ProCast data base)

Experimental approach: Processing

Directional solidification with

constant solidification velocity

and

constant temperature gradient ahead of s/l interface

and

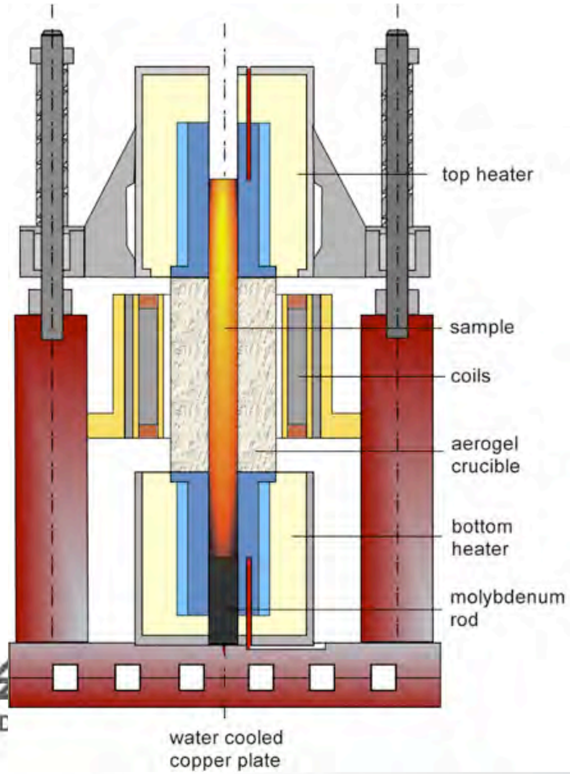
flat isotherms (aerogel crucibles)

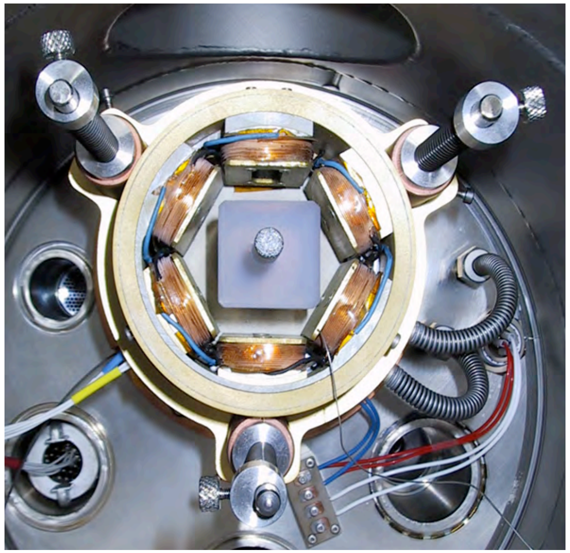
Process parameters:

-v = 0.015 – 0.15mm/s

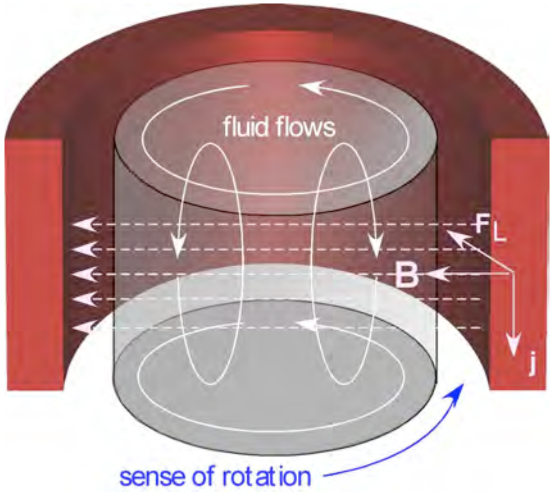
-G = 3K/mm

-fluid flow induced by RMF



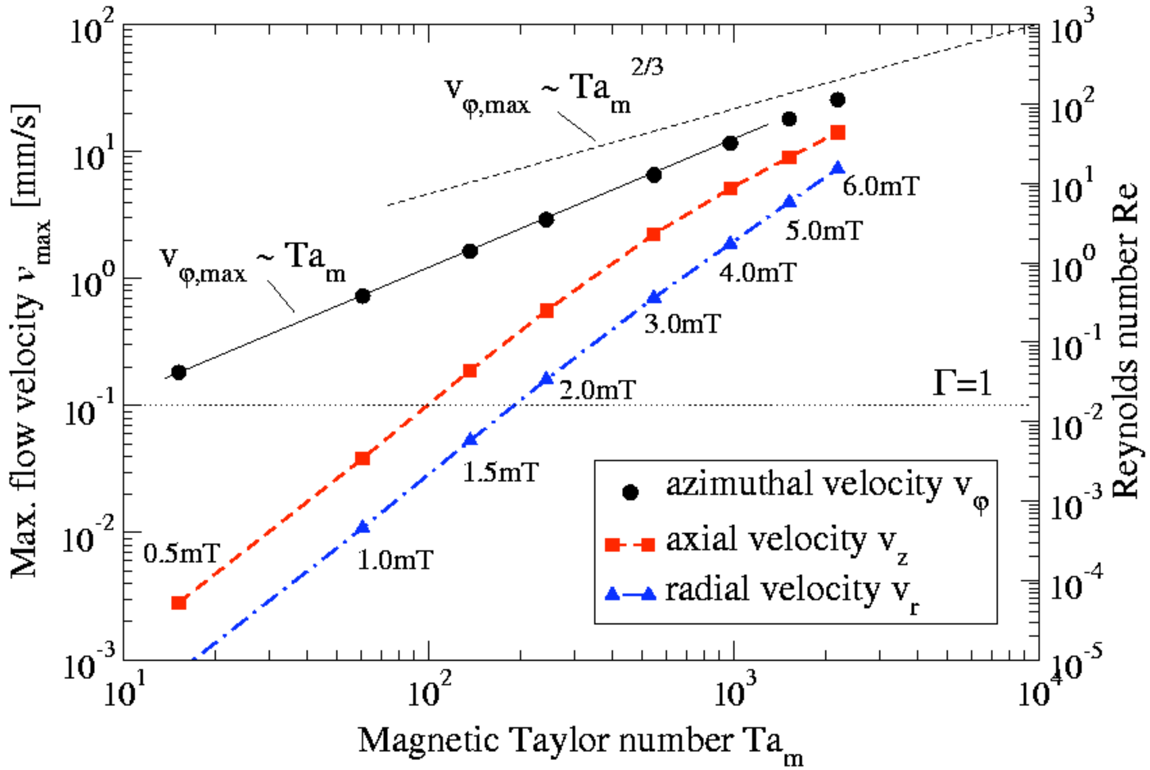


The RMF parameters used



Parameters used:

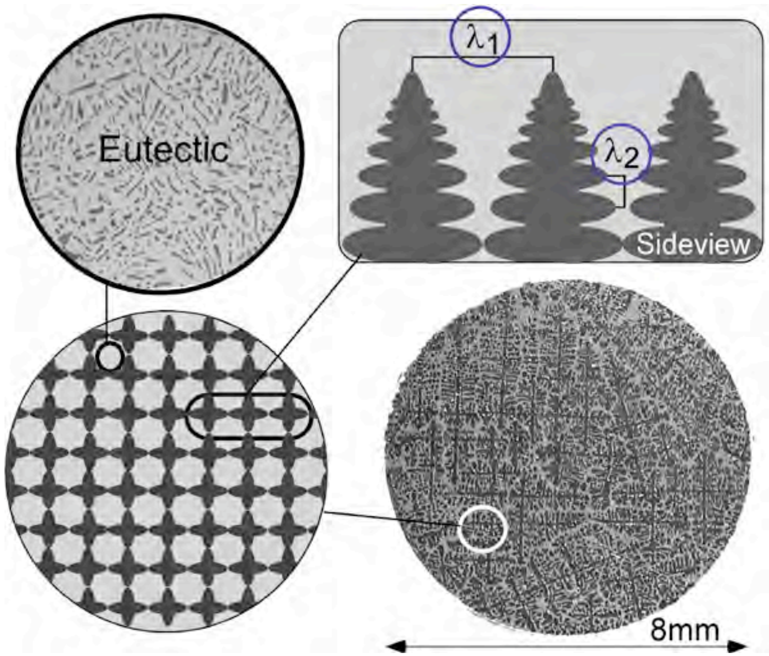
- R = 4mm
- G = 3 K/mm
- v_G = 0.1mm/s
- B = 1-6mT
- f = 50Hz
- h = 100mm
- **Ta ≤ 2500**
- **Re ≤ 50**

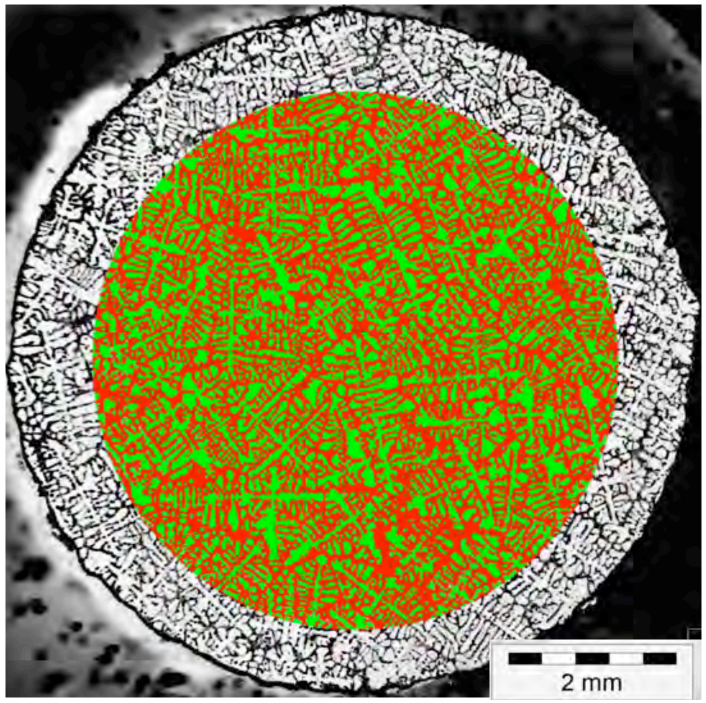


M. Hainke, PhD-thesis, U Erlangen-Nuremberg, 2004

Al-7wt.%Si

Microstructural evaluation





Primary dendrite stem spacing λ_1

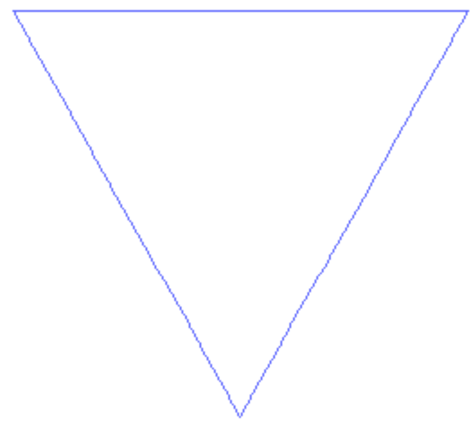
secondary dendrite arm spacing λ_2

Specific surface area $S_V = A_{\alpha e}/V$

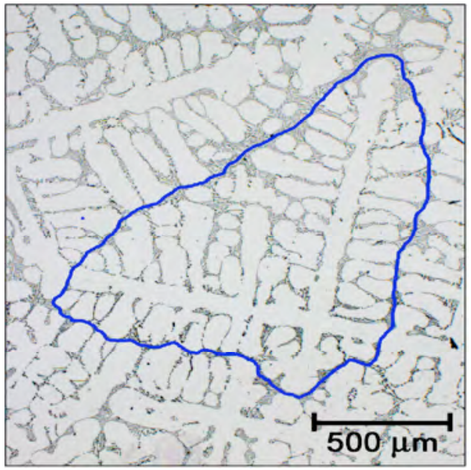
Note: $S_V = 2\overline{H}$ with $\overline{H} = \frac{\partial A}{\partial V}$ = average curvature

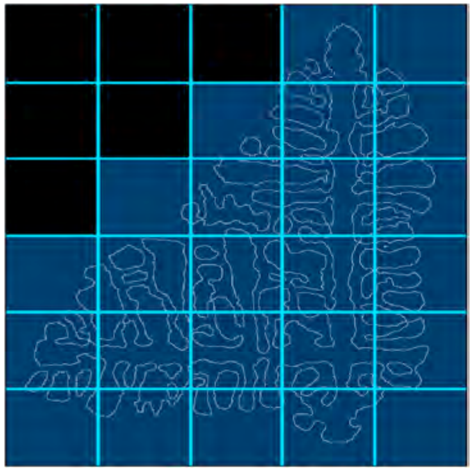
Fractal dimension measurement

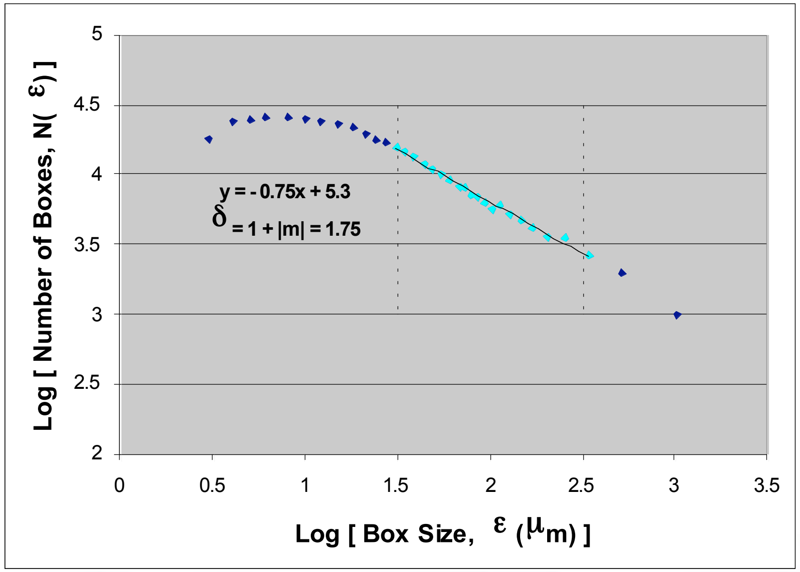
- a descriptor for branching?



Method:
- Outline a single dendritic structure in a section
- Characterize its interface to the eutectic matrix with a 1pixel interface
- Measure the interface length by the box counting method
  - boxes needed to cover the whole interface. Vary the box size.
- Plot: Interface length as a function of box size
- The fractal dimension of the interface is the slope of the straight line in the range of 55 μm to 550 μm
- Note: The fractal dimension in a 2D section is that in 3D too.



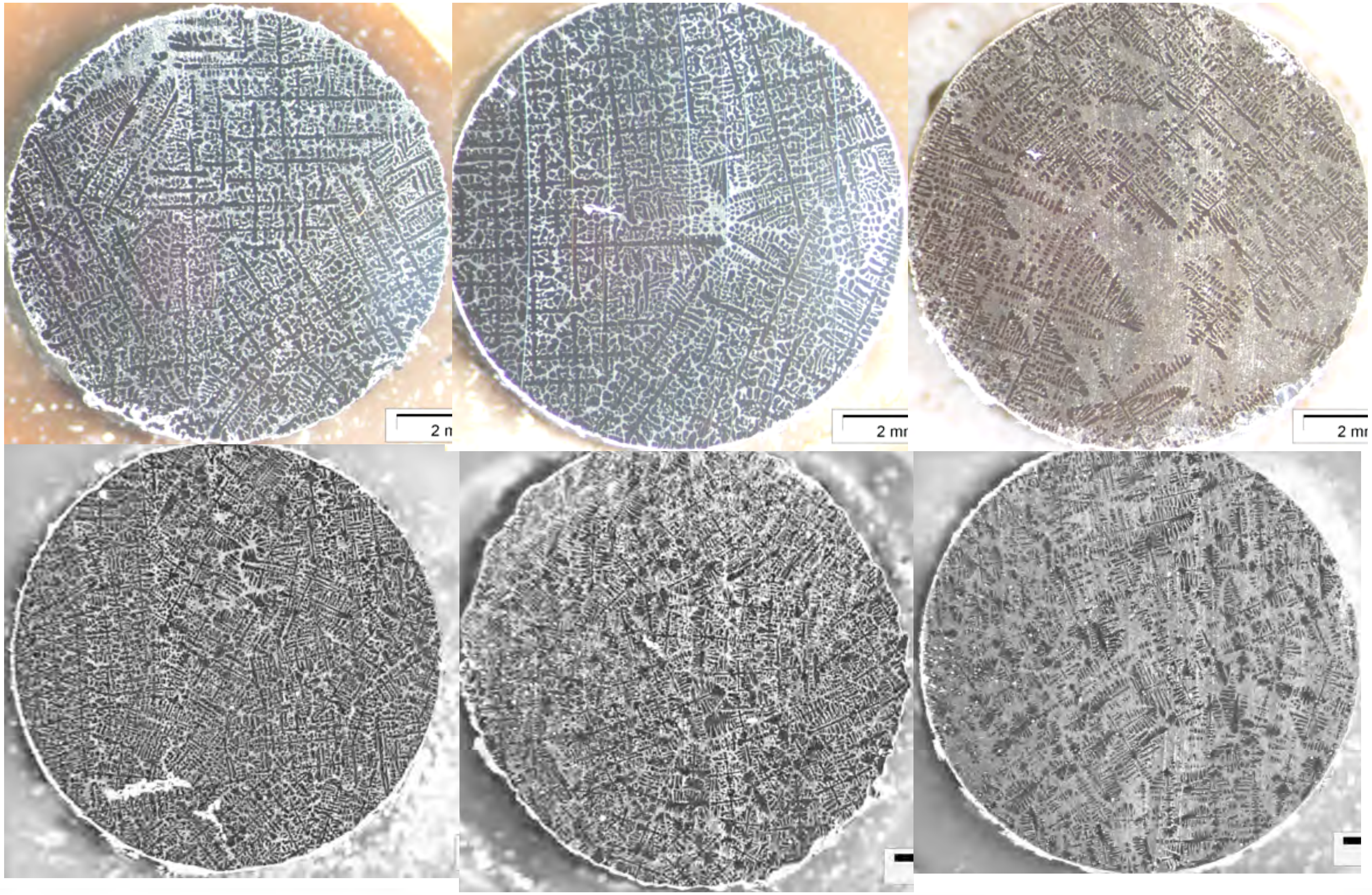




Microstructures

Typical Microstructures – effect of solidification velocity

AlSi5 | AlSi6 | AlSi9

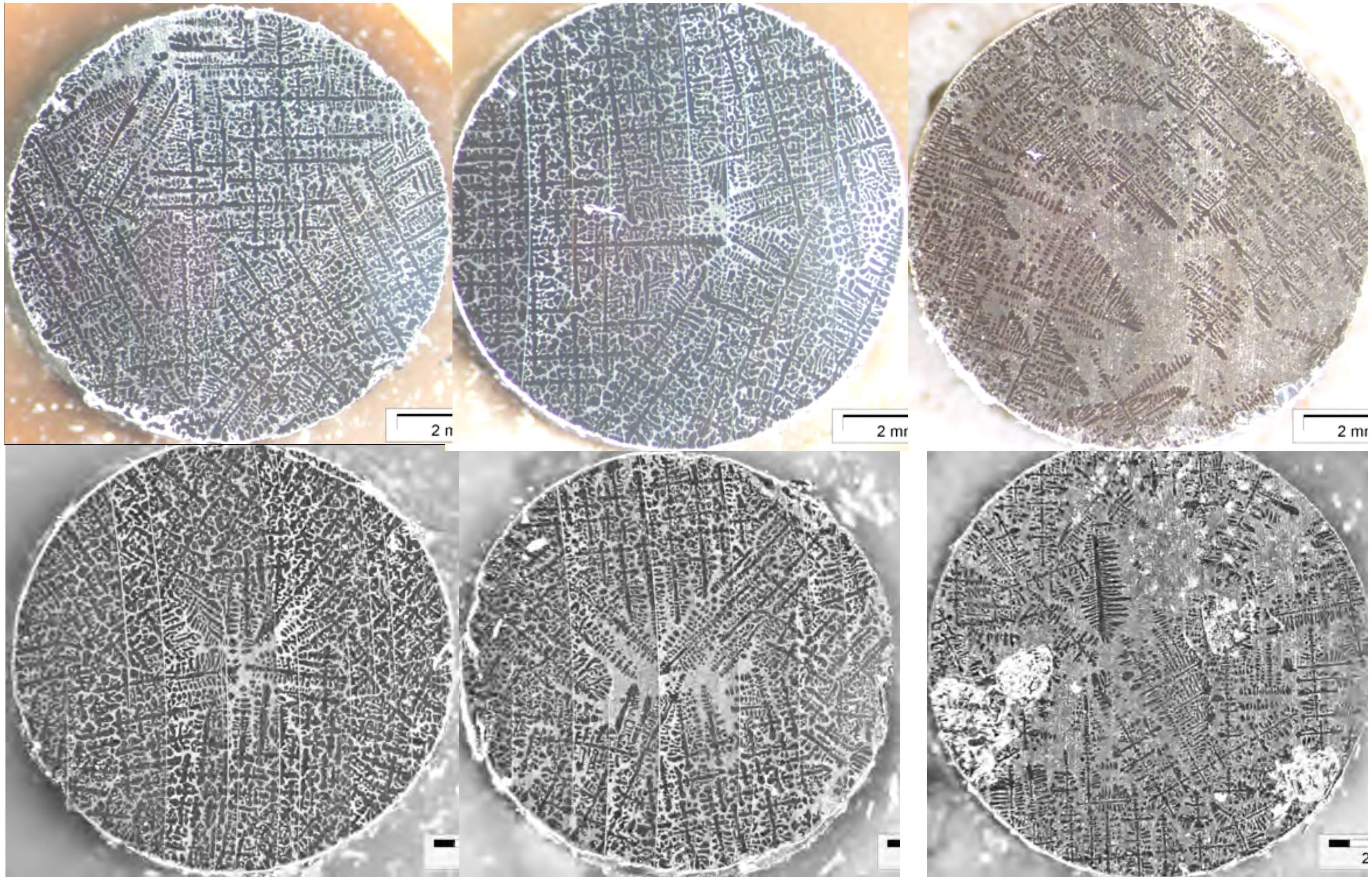


B = 0mT
v = 0.03mms
G = 3K/mm

B = 0mT
v = 0.15mms
G = 3K/mm

Effect of RMF: macrosegregation

	AlSi5	AlSi6	AlSi9



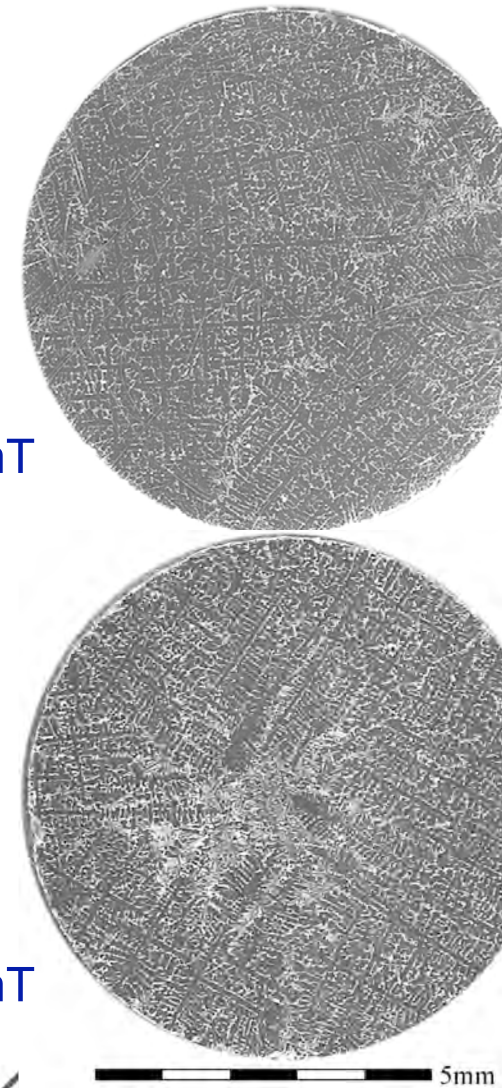
B = 0mT
v = 0.03mms
G = 3K/mm

B = 6mT, 50Hz
v = 0.03mms
G = 3K/mm

Flow effect: Macro-segregation in AlSiCu alloys

0 mT

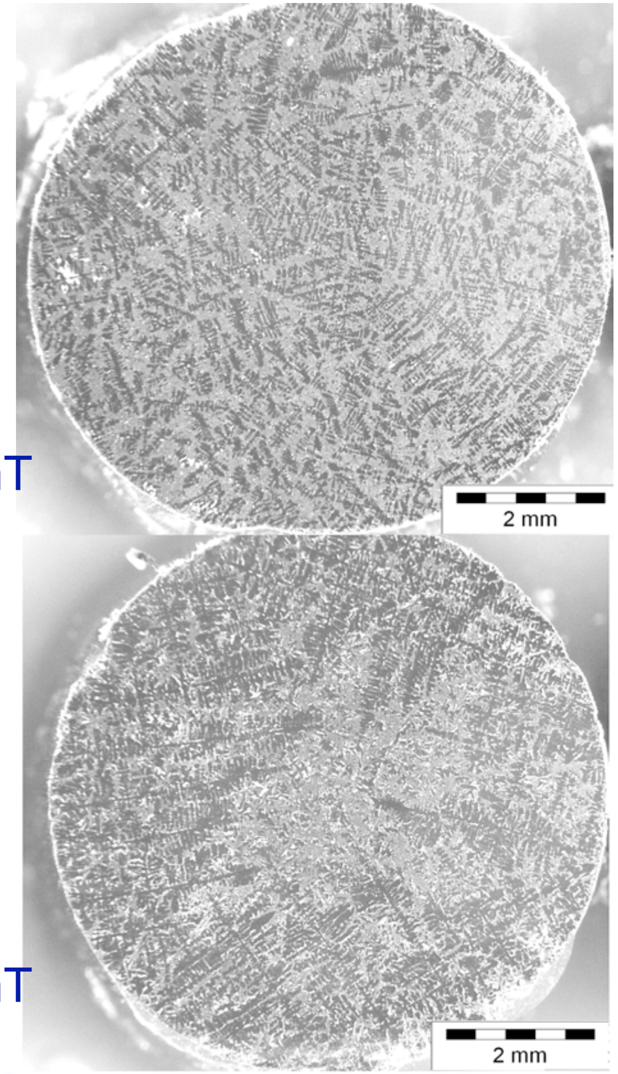
6 mT



Al - 6wt.%Si - 4wt.%Cu
0.03 mm/s   G = 3K/mm

0 mT

6 mT



Al - 9wt.%Si - 4wt.%Cu
0.02 mm/s   G=3 K/mm

Macro-segregation quantitatively

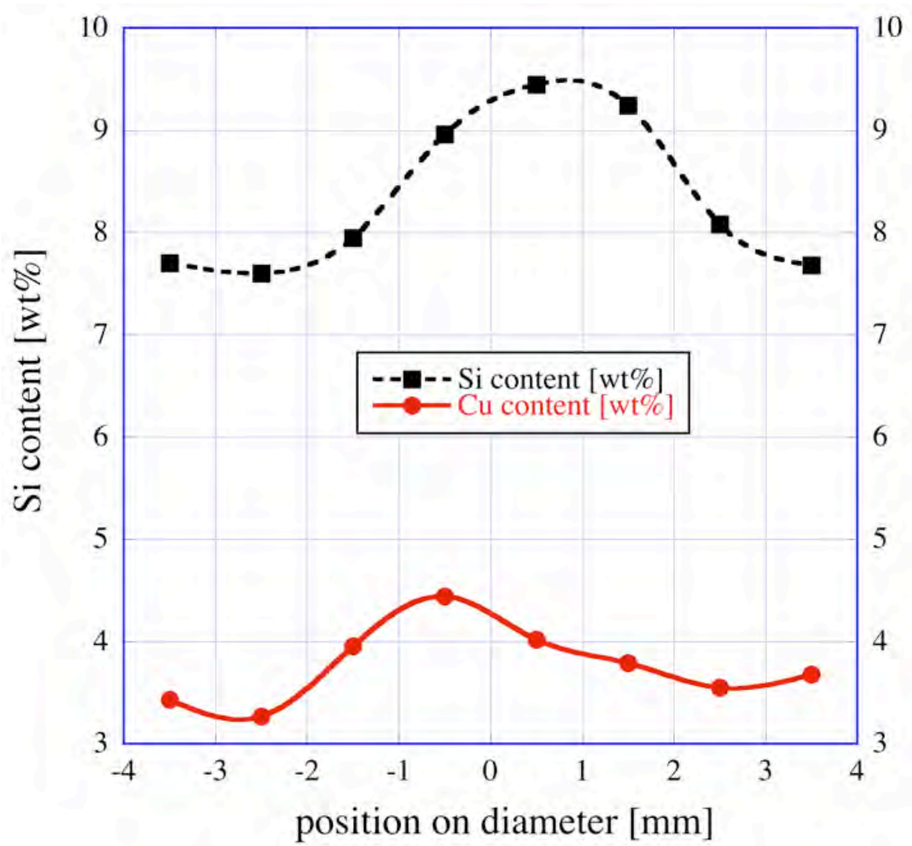
- Segregation of Silicon and Copper towards the sample centre

  (measurement by EDX in SEM with calibration standards)

- No axial segregation for both elements measured !

- Effect of secondary flows

- Modelled for these alloys by Hainke and Dagner (U Erlangen) and Yves Fautrelle (SIMAP/EPM)



AlSi9Cu4, v=0.02 mm/s, B=6 mT
Average of 8 sections along the processing length

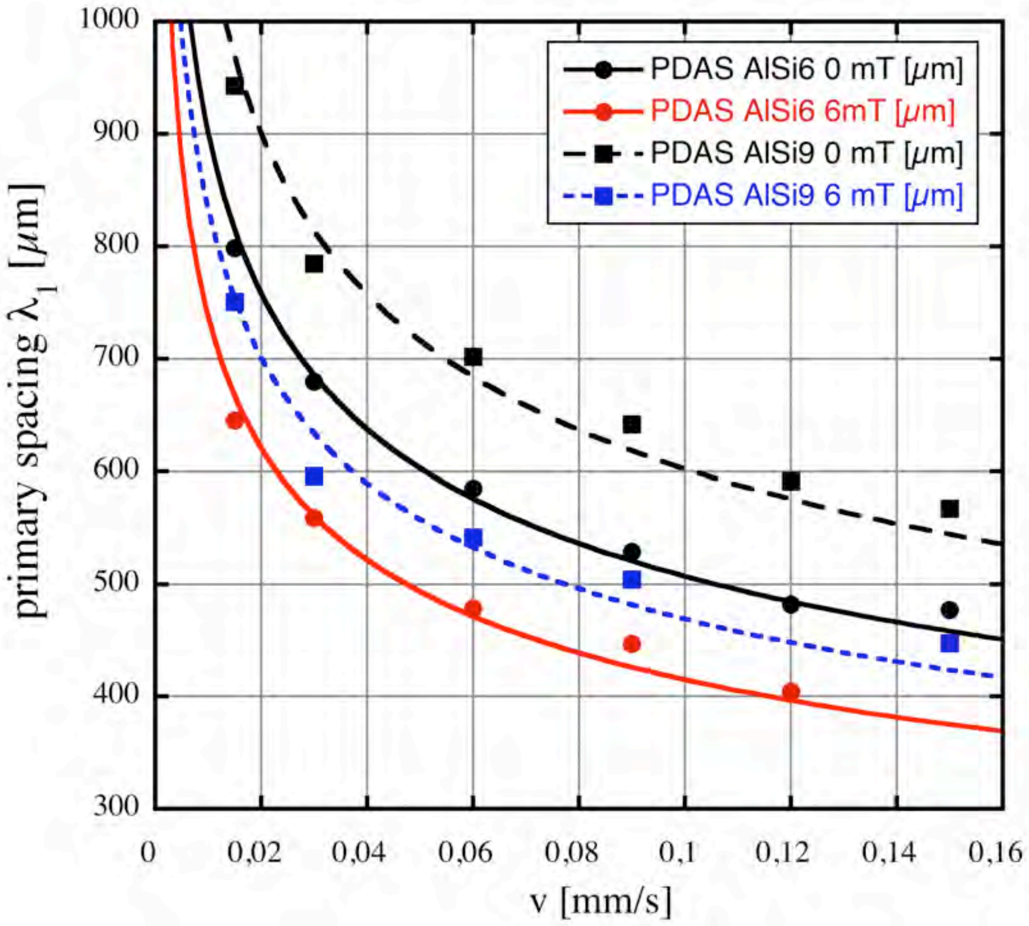
Microstructure parameters

Primary spacing AlSi alloys

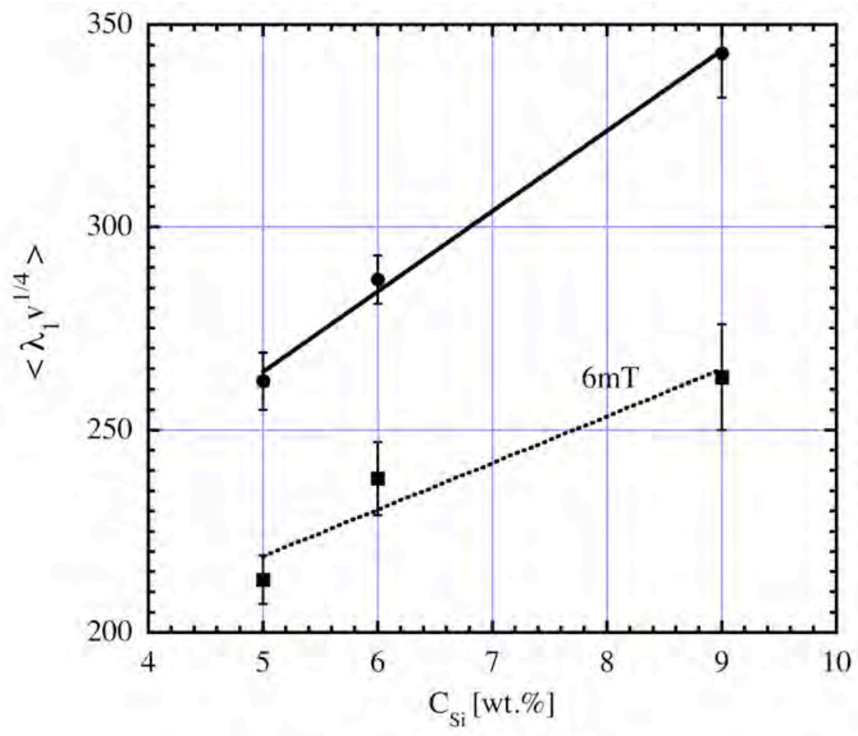
- Primary dendrite stem spacing depends on solidification velocity as an inverse fourth power, as expected (LGK)

$$\lambda_1 = \left(\frac{72\pi^2 \Gamma \Delta c_0 m_L D_l}{k} \right)^{1/4} \frac{1}{G^{1/2}} \frac{1}{v^{1/4}}$$

- Fluid decreases the primary spacing (PDS)
- Same observations made in AlSiCu and AlSiMg alloys



Primary spacing AlSi



Observations:

1. Increase of of the rate constant with Si content as expected. In the LGK picture

$$< \lambda_1 v^{1/4} > \;\propto\; (D_L c_0)^{1/4}$$

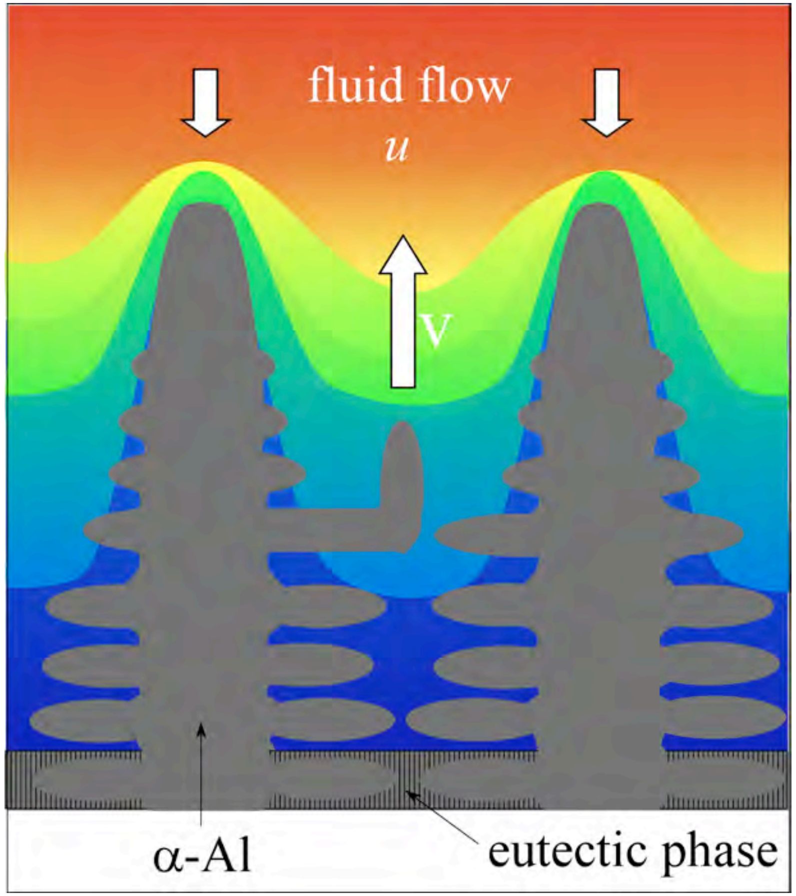
2. and taking into account the eutectic fraction we arrive at

$$\lambda_1 = \frac{a + b(c_0 - c_\alpha)}{\sqrt{G} v^{1/4}}$$

$$a,b = \text{const.}(D_L, m_L, \Gamma, k)$$

3. Flow reduces the constant term: thus fluid flow is not treatable as an effective diffusion constant enhancer

Primary spacing ↔ fluid flow



Coupling of different effects :

- interdendritic convection
- constitutional supercooling between primary stems
- locally varying permeability of the mush

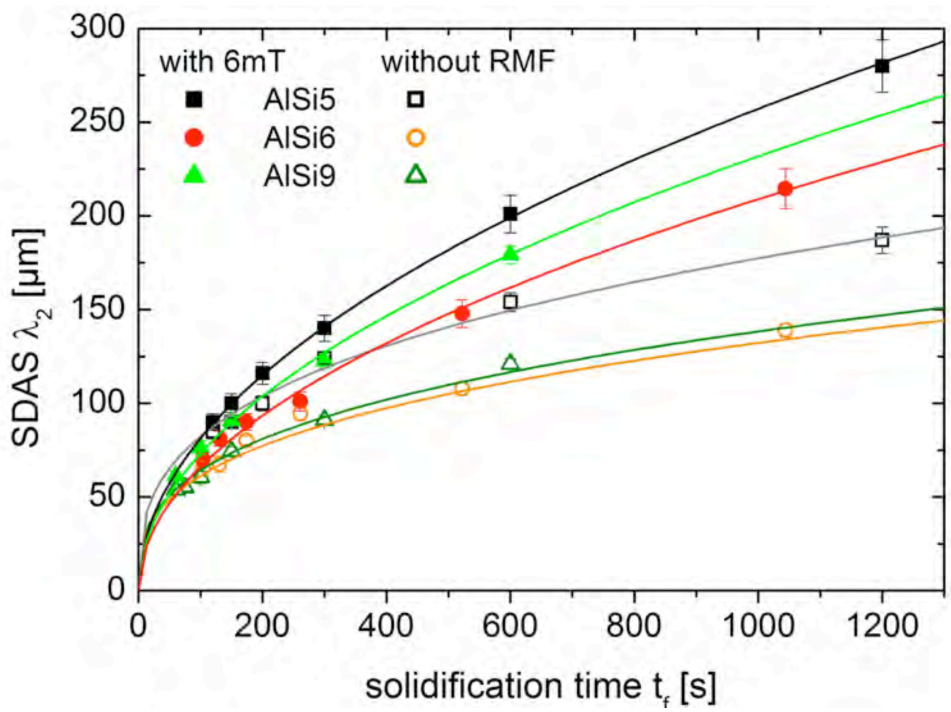
General idea:

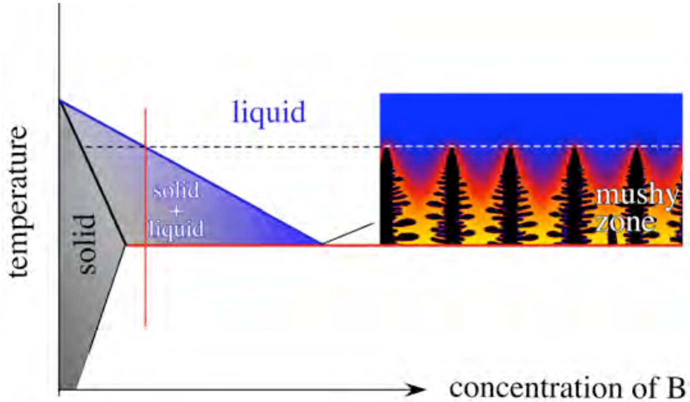
Tertiary arms become new primary arms due to constituional supercooling enhancement between dendrites

→

primary spacing decreases

Secondary dendrite arm spacing





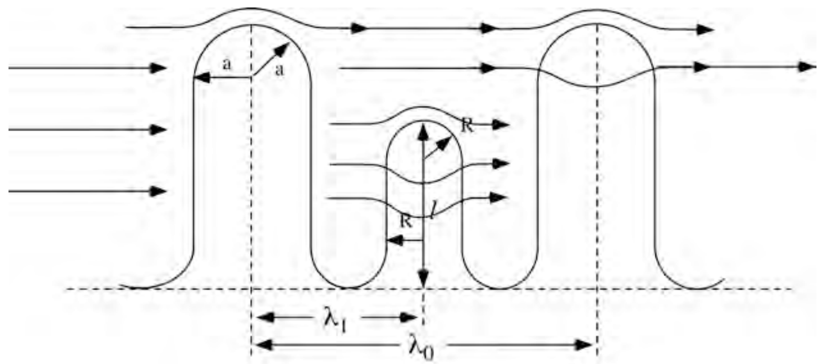
C_o [wt.%]	M [µm^3/s]
AlSi5	11.24
AlSi6	10.36
AlSi9	8.62

$$M = \frac{D\Gamma \ln(c_e / c_0)}{m_l (1-k)(c_0 - c_e)}$$

1. λ_2 follows classical coarsening law $t_f^{1/3}$ in the diffusive case
2. with increasing c_o the SDAS decreases
3. Flow enhances coarsening and a change in kinetics ($t_f^{1/3} \rightarrow t_f^{1/2}$) !

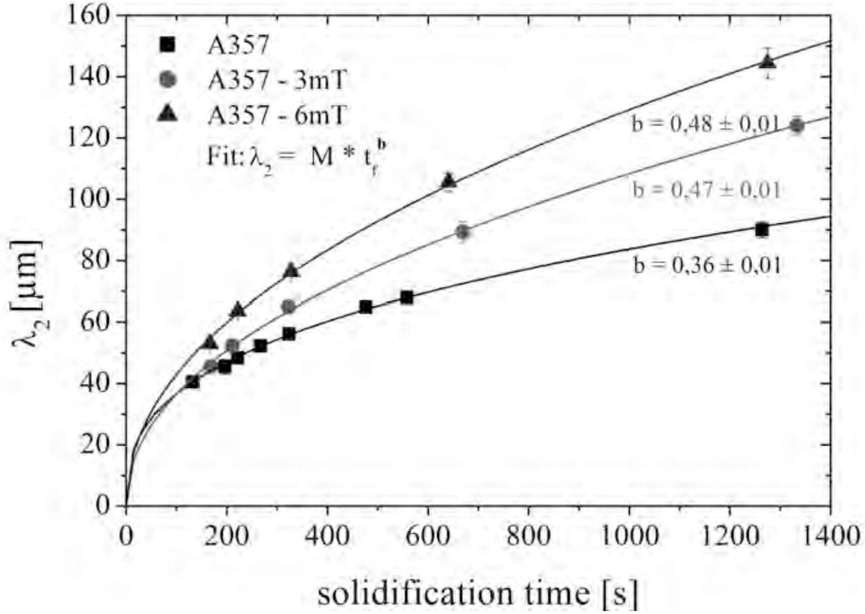
Interpretation

- Fluid flow accelerates dendrite arm coarsening (Stokes type flow around secondary arms from the mush tip towards the bottom)
- Boundary layer flow solution (Ratke, Thieringer, Diepers, Beckermann) yields a new kinetic law



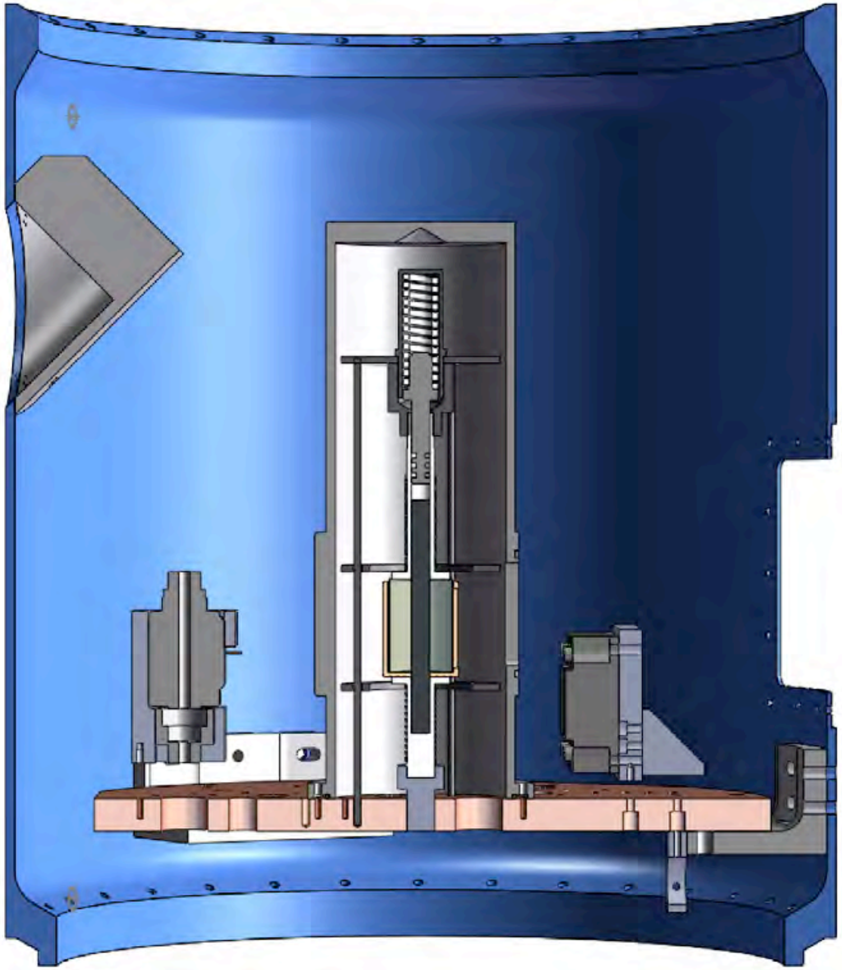
$$\lambda^2 = \frac{1}{2} M \left(\frac{P_R(f_S)\nabla p}{D\eta} \right)^{1/3} t_f = K\, t_f$$

$$K(B_2) = K(B_1) \sqrt{\frac{1 - c_0(B_1)/c_e}{1 - c_0(B_2)/c_e}} \left(\frac{B_2}{B_1} \right)^{2/3}$$



K=5.7 in A357 K_{exp}= 4.8
K=6.3 in AlSi6Cu4 K_{exp}= 4.9

Comparison with microgravity results



Results of four µg-experiments with AlSi6:

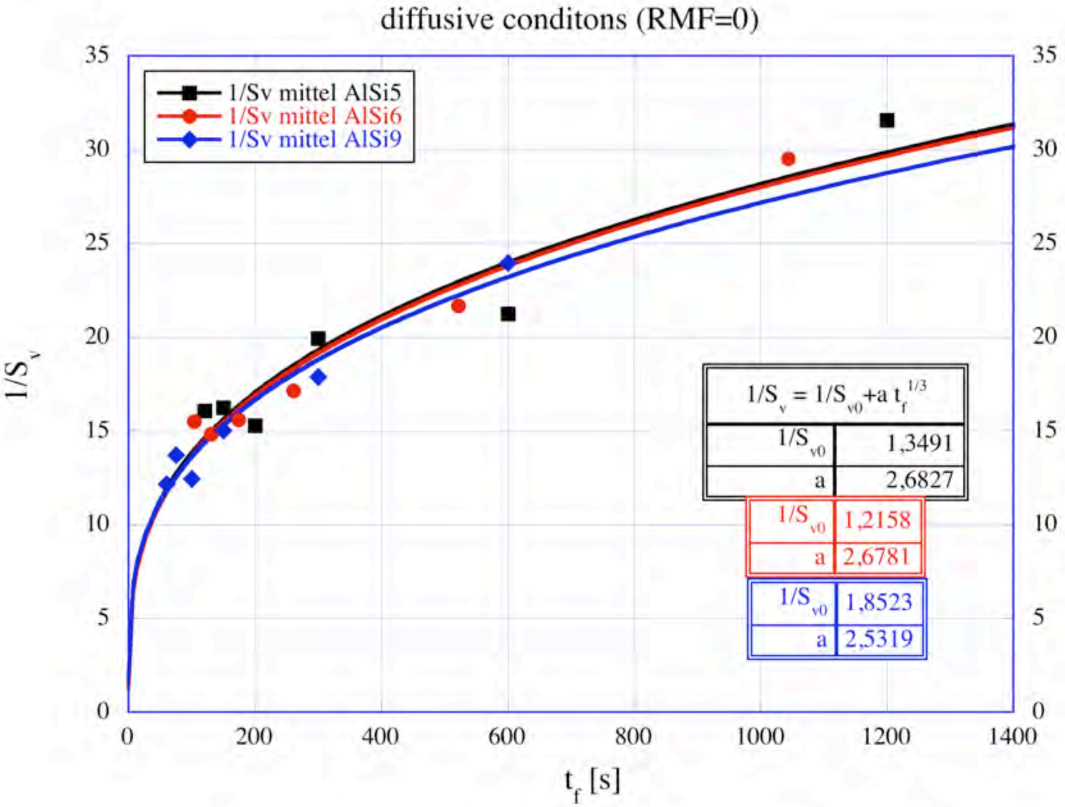
TEXUS 39, TEXUS 41, Maxus7 and Mapheus yield
3 values for diffusive growth and
2 values for µg+RMF

λ_2 follows classical coarsening law $t_f^{1/3}$ in the diffusive case

Flow enhances coarsening and a change in kinetics as measured in the lab, but not disturb by natural convection

Further experiments in the MSL of the ISS have started this month (Nov 7th) and will continue January 2010.

Specific surface area S_v – diffusive case



S_v scales with solidification time t_f

$$\frac{1}{S_V} = \frac{1}{S_{V0}} + a \cdot t_f^{1/3}$$

$$a = \frac{\sqrt[3]{B \cdot M(T, c_0, U/v)}}{2}$$

$$\lambda_2^3 = \lambda_{20}^3 + BMt_f$$

$$M = \frac{D\Gamma \ln(c_e/c_0)}{m_l(1-k)(c_0 - c_e)}$$

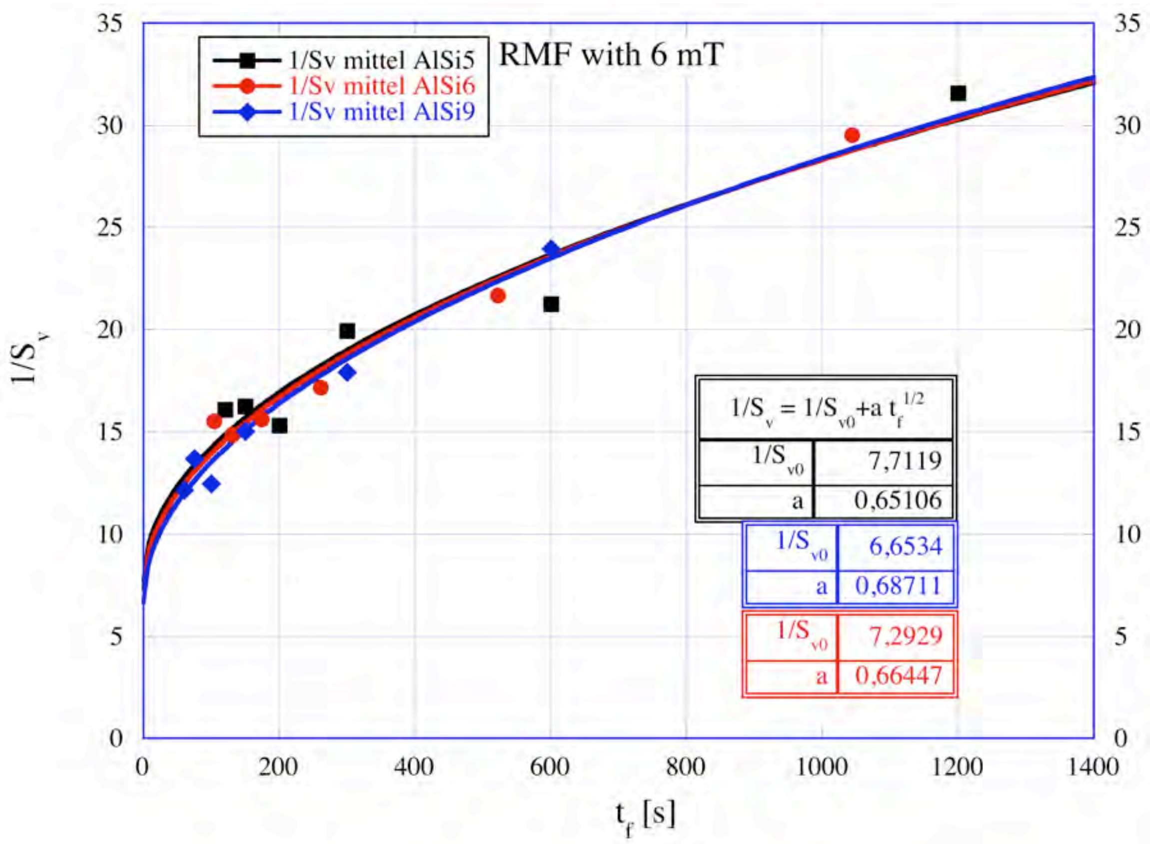
$$B \cong 5.5$$

1. S_v independent of sample section
2. Identical time relation:

$1/S_v \sim t_f^{1/3}$

C_o [wt.%]	M [µm³/s]	a_{theo}	a_{exp}
AlSi5	11.24	1.98	2.68
AlSi6	10.36	1.92	2.68
AlSi9	8.62	1.81	2.53

Specific surface area S_v – convective case



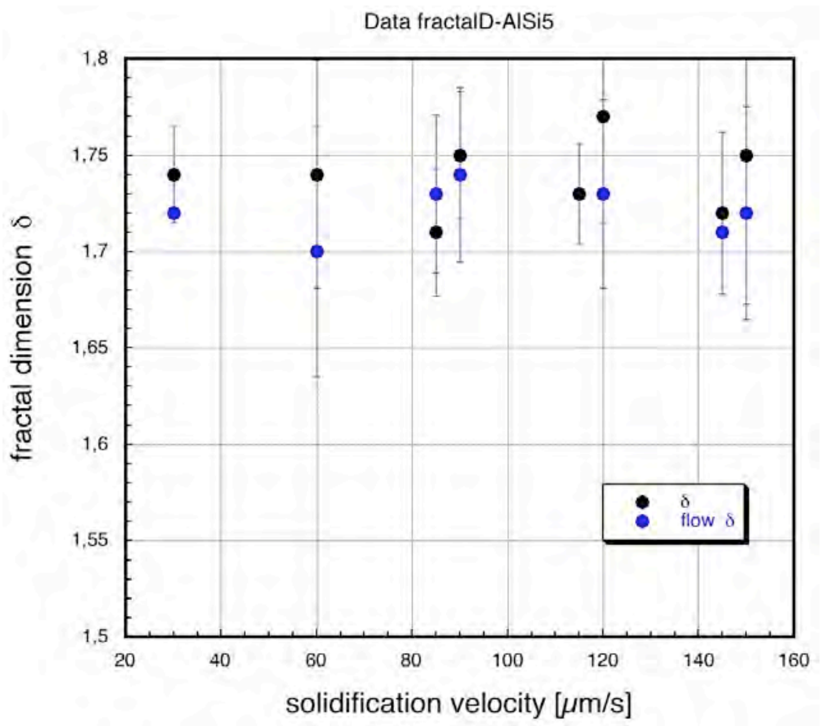
Also a scaling relation:

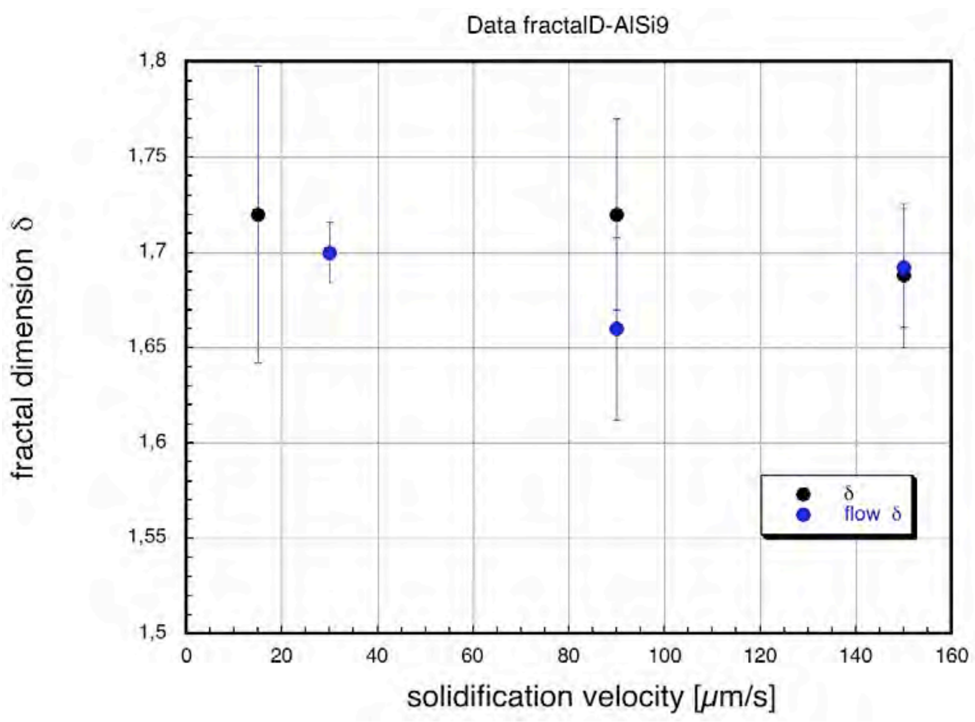
$1/S_v \sim t_f^{1/2} \sim \lambda_2$

But:
All curves fall together!

And one could equally well fit a cube root law.

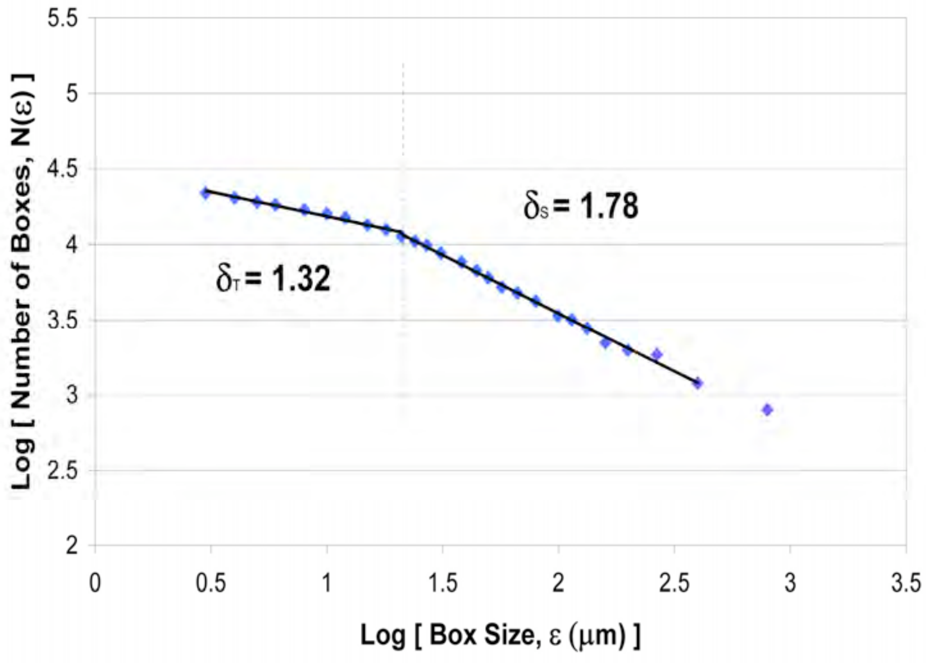
Fractal dimension





Fractal dimension of selected dendrites in cross sections averages of 4 to 20 dendrites, mostly 6 to 14.

Fractal dimension



For some dendrites, two linear regions were apparent. After Kaye these are

- structural fractal (δ_S) = overall morphology
- textural fractal (δ_T) = surface roughness

Observations by others:
Xenon dendrites
δ = 1.42 ± 0.05, independent of undercooling and aging time (Bilgram *et. al.*)

Ni-base superalloys
δ= 1.228 – 1.418 (Yang et al)
δ increases with solidification velocity

Unexpected result:

There is no effect of flow on the fractal dimension.

Interpretation?

Bisang U., Bilgram J.H. J. Cryst. Growth 166 (1996) 207-211.
Yang A., Xiong Y., Liu L. Sci. Tech. Adv. Mat. 2 (2001) 101-103.
Kaye, B.H. *A Random Walk Through Fractal Dimensions* VCH Publishers, New York 1989.

Conclusions

- Fluid flow created by RMF fields induces in solidification of AlSi and other AlSi-base alloys
  - Reduced primary dendrite spacings
  - Increased secondary dendrite arm spacing and modifies the coarsening kinetics
  - radial macro-segregation of alloying elements (not shown)
  - Cannot be thought as simply enhancing mass transport
- Specific surface area of primary phase is less affected by fluid flow than SDAS
- Fractal dimension of dendrites not modified by fluid flow

- Further experiments with much better statistics concerning
  - Specific surface area (high resolution micrographs) and fractal dimension are necessary

  Such evaluations are ongoing at the moment

- Microgravity experiments provide a convention free environment confirming lab results and building benchmark experiments.
- Future µg experiments on the ISS and sounding rockets etc. will enlarge the data base.