METRO
MEtallurgical TRaining On-line

Growth of solid phase

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CzUT

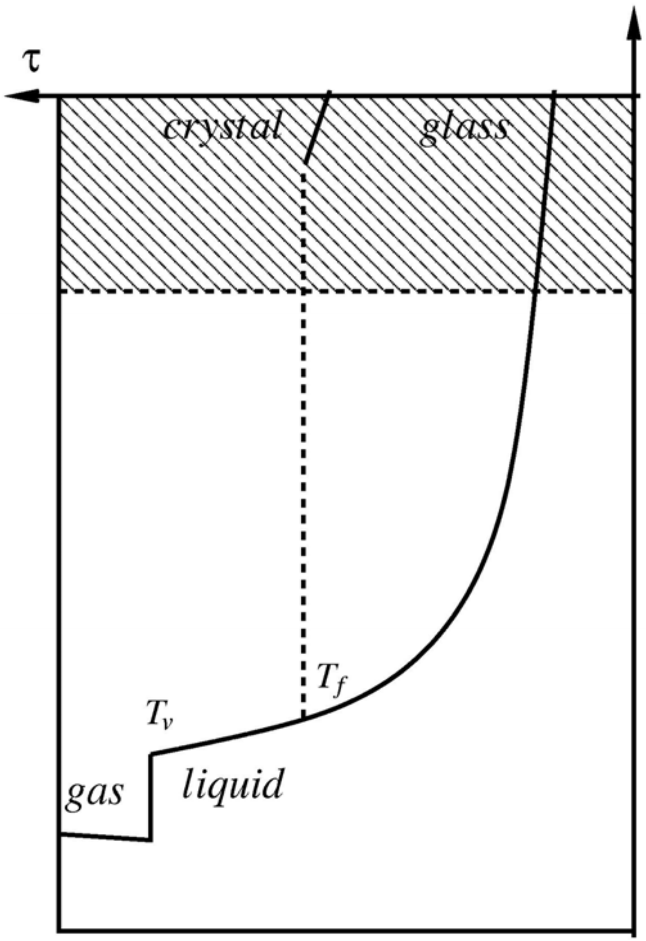
Education and Culture

Outline

- Introduction
- Physical background
- Dendritic and eutectic growth
- Interaction between phases and grains
- Single grain growth
- Keypoints and sources

Once, the nucleus has appeared
it starts to grow

What is a solid phase?



"A **phase** is a constituent completely homogeneous both physically and chemically separated from the rest of the alloy by definite bounding surfaces"

Decrease in temperature:

Glass formation

– continuously increase in viscosity

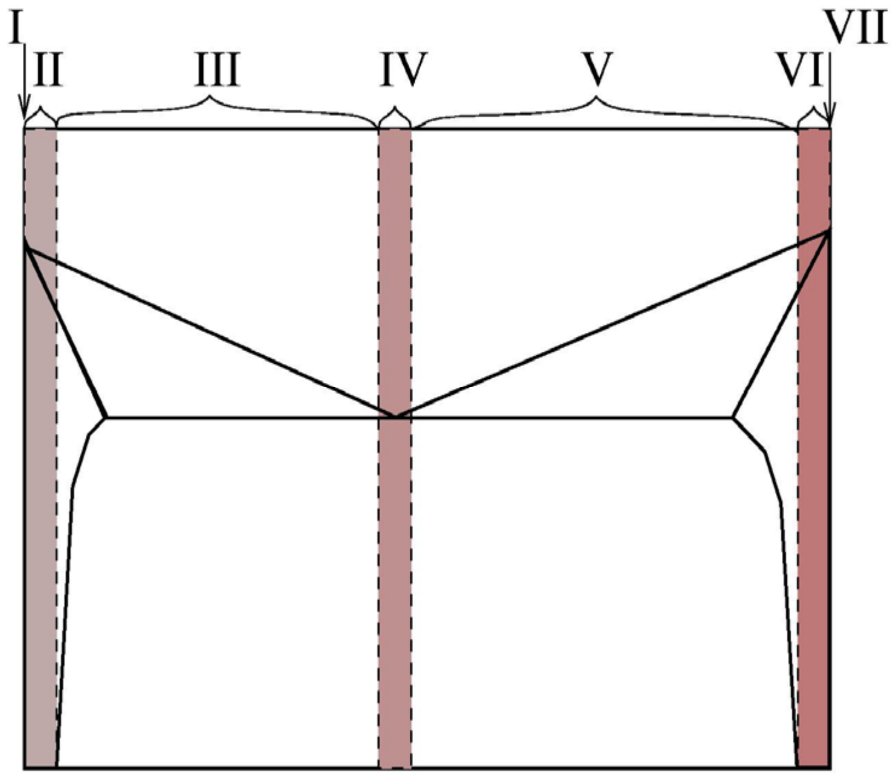
Crystallization

– discontinuously increase in viscosity

What is microstructure?

Microstructure
is defined by
phases and morphology

Phase diagram and microstructure



Is phase diagram enough?

When or how fast
the phase transformation occur?

Thermodynamics

+

kinetics

=

complex microstructure

Introduction

The crystal growth is limited by:

- the kinetics of atom attachment to the interface,
- capillarity,
- diffusion of heat and mass,
- convection.

Physical background

(What affects the crystal growth process?)

Transport processes

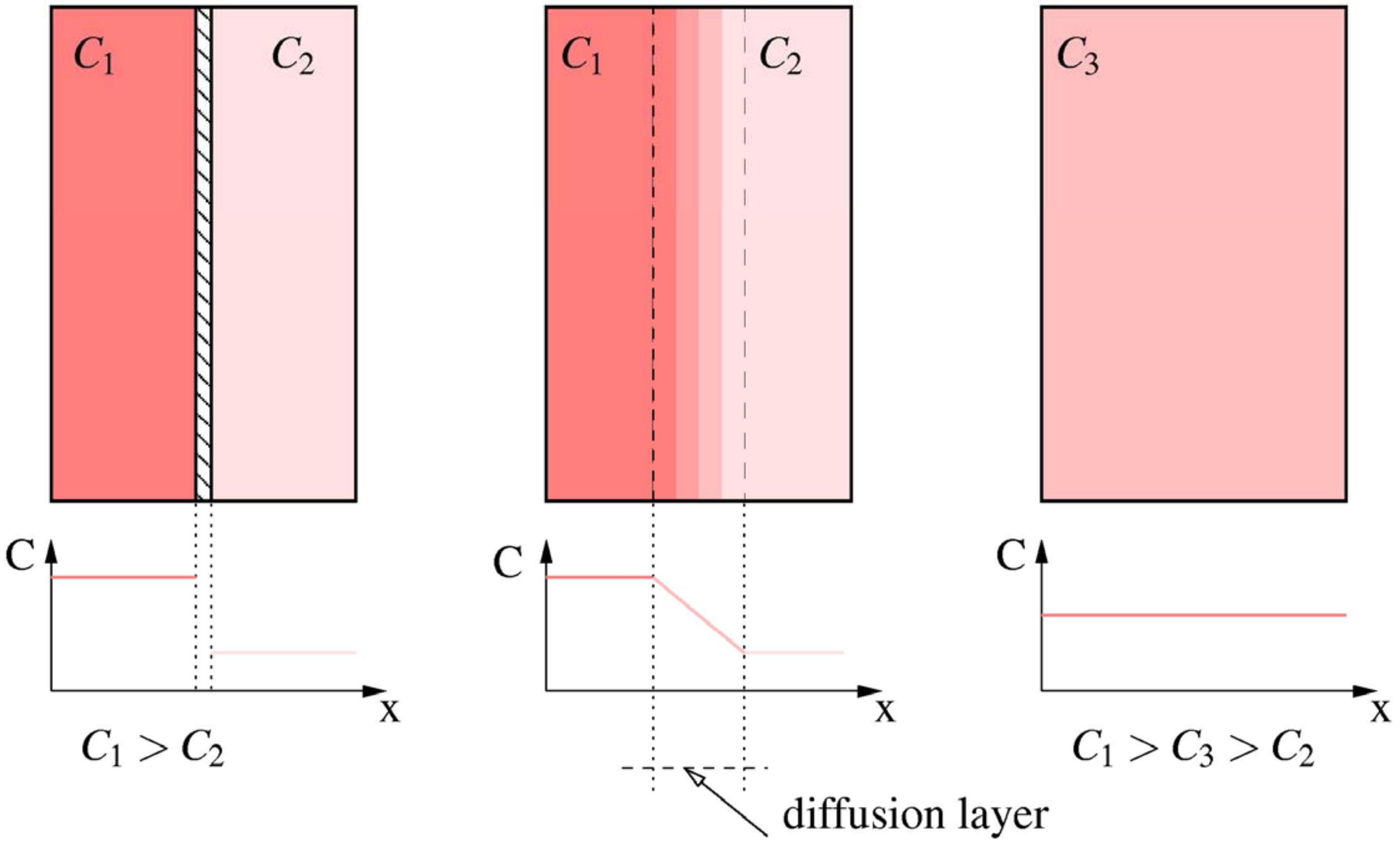
$$\frac{\partial}{\partial t}(\rho\phi) + \nabla(\rho V\phi) = \nabla\cdot(\rho\Gamma\nabla\phi) + S$$

where:

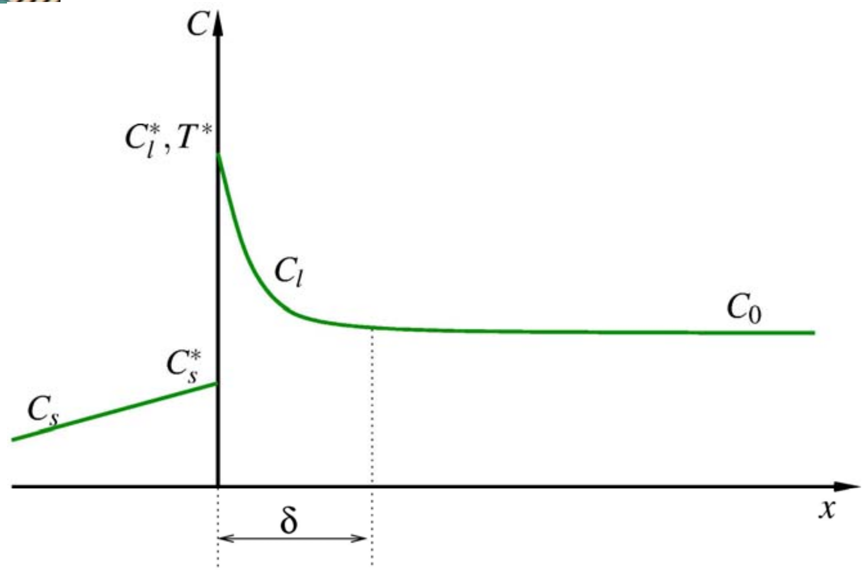
∇ - del operator
t -time
ϕ -the phase quantity
ρ - density
$\mathbf{V}$ - velocity vector
Γ - general diffusion coefficient
S -source term

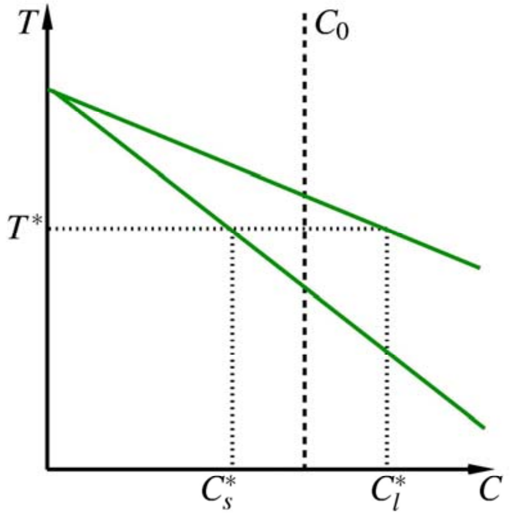
quantity	mass	energy	species	momentum
ϕ	1	H	C	$\mathbf{V}$
Γ	0	α	D	ν

Diffusion



Diffusion process





$$C_s^* = kC_l^*$$

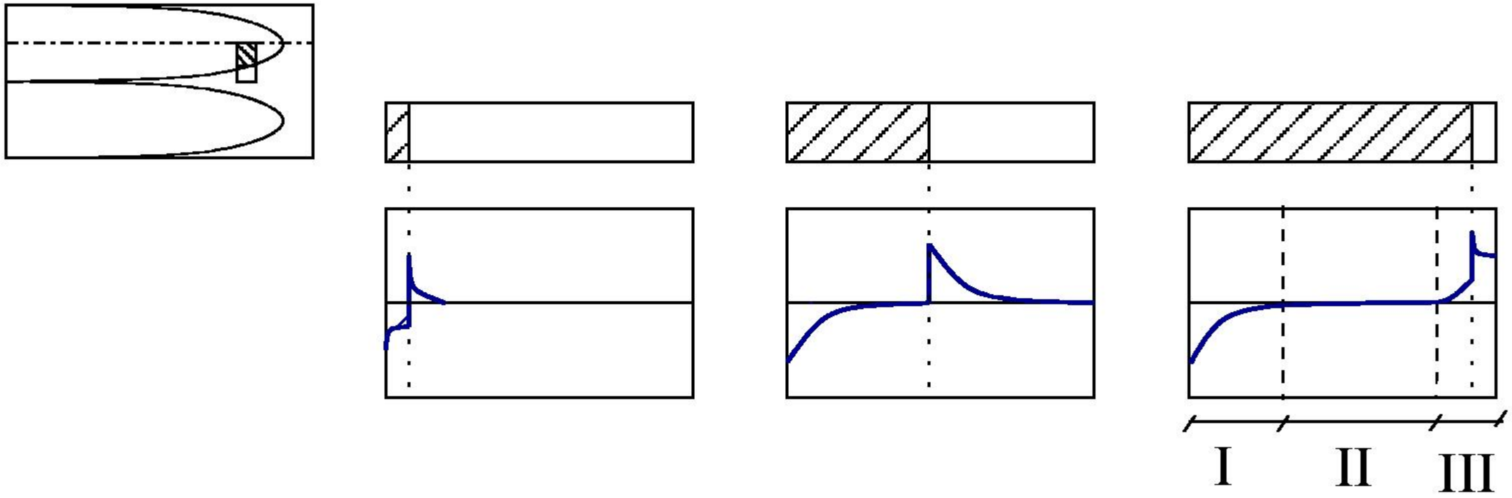
type of diffusion	diffusing species	type of phase	layer thickness[mm] at V = 0.01mm/s
solutal	substitutional atom	crystal	10^{-4}
	interstatial atom	crystal	10^{-1}
	either	liquid	10^{0}
thermal	heat	crystal	$> 10^2$
		liquid	$> 10^2$

Microsegregation

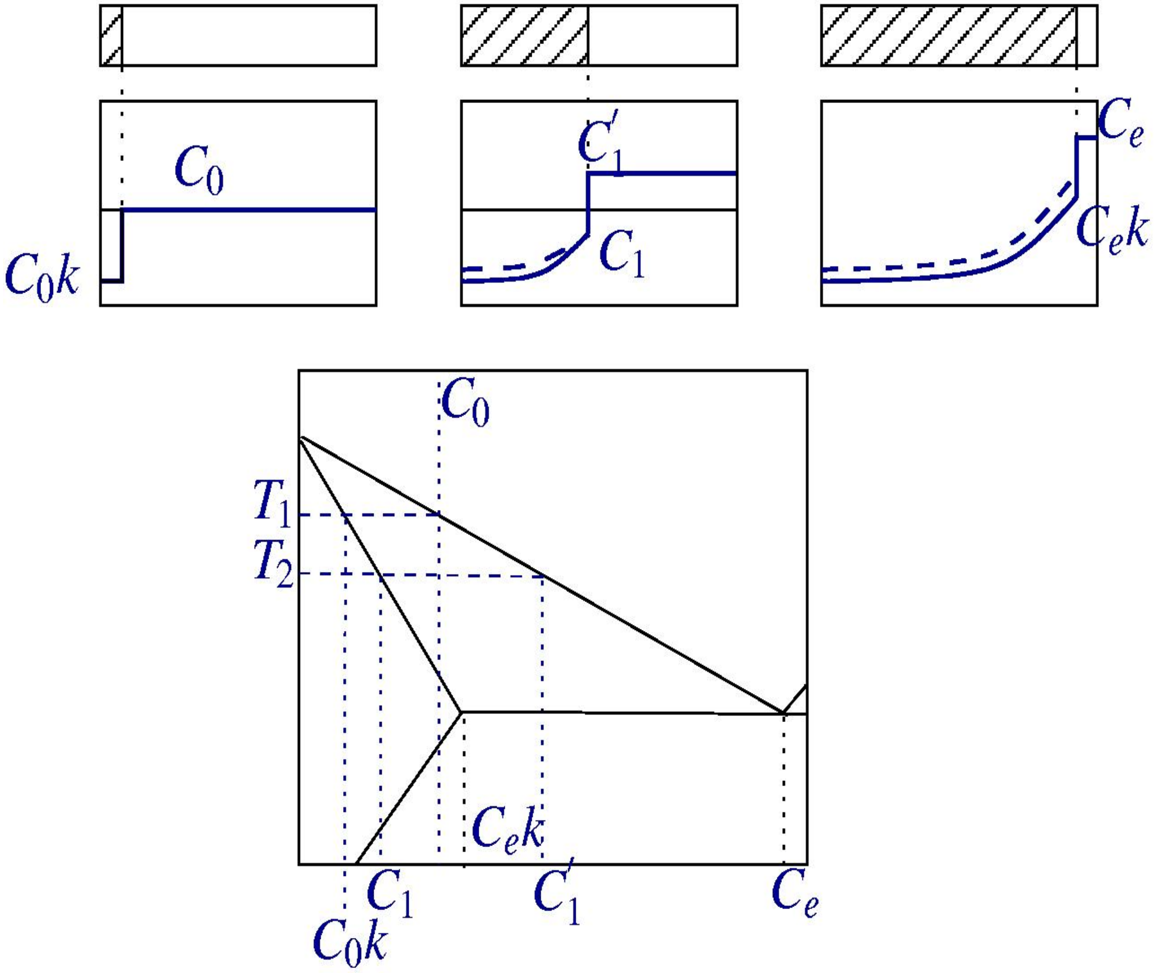
Analysis of the solute redistribution:

- equilibrium lever rule
- no diffusion in solid
- partial diffusion in solid
- mixing in liquid
- limited diffusion in liquid
- complete diffusion in liquid

Microsegregation



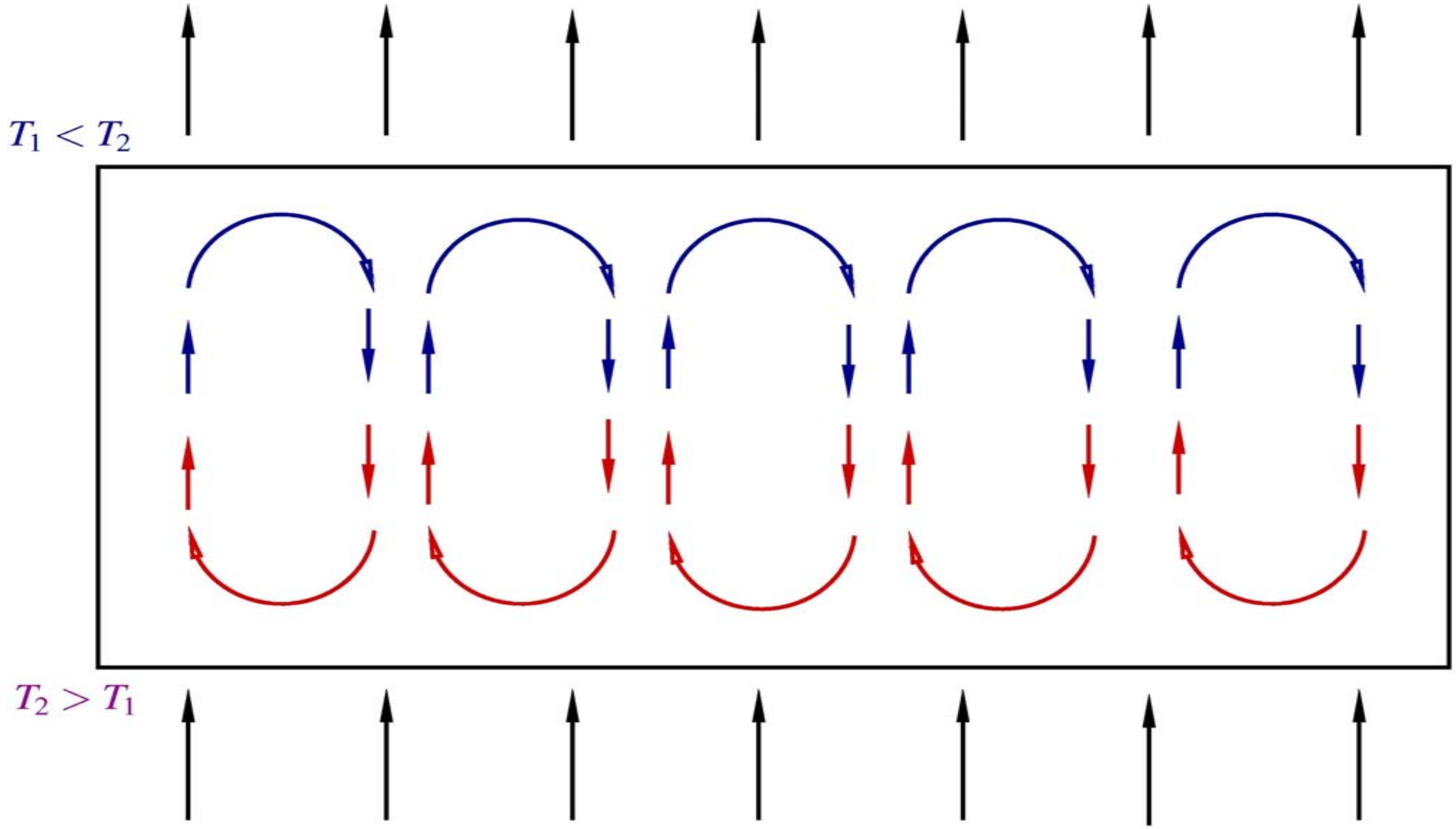
Microsegregation



Heat transport

- Without heat removal there is no solidification
- Constitutional undercooling can lead to the dendritic growth
- Rate of solidification affect the CET
- Convection affect the final microstructure on micro and macroscale

Convection



Convection

Driving forces for convection:

- **Internal** (shrinkage flow, natural convection, capillary forces, formation of gas bubbles, and deformation of solid phases because of thermal stress)
- **External** (pressure gradient, electric, magnetic forces, external movement surrounding the melt)

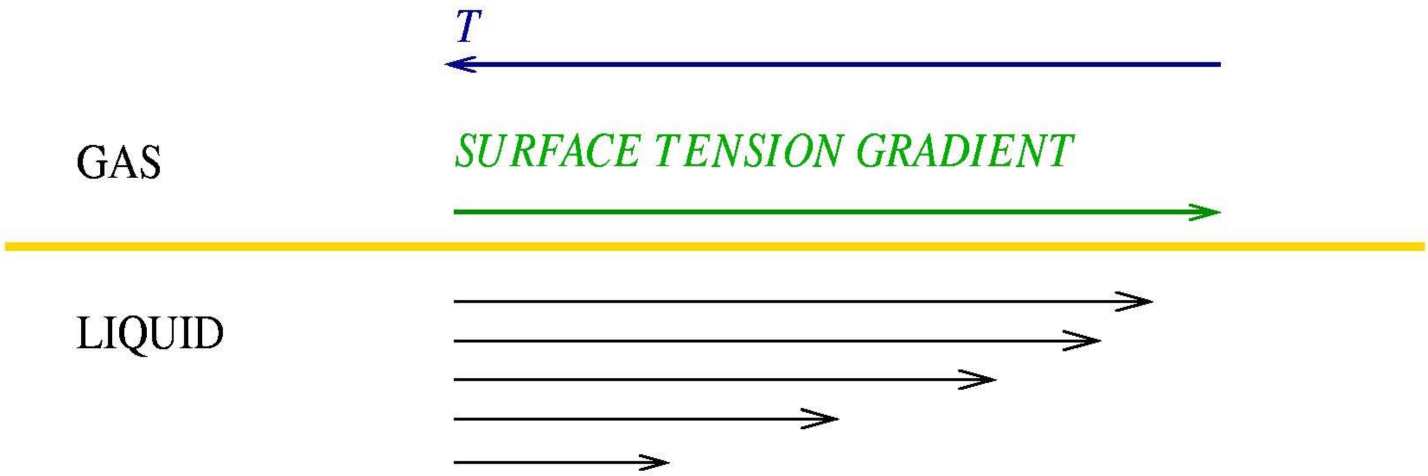
Convection

Natural convection

- it comes from buoyancy forces
- density variation lead to the current flow, which is temperature and concentration dependent
- convection affect the temperature and concentration field
- convection may lead to the micro and macrosegregation

Convection

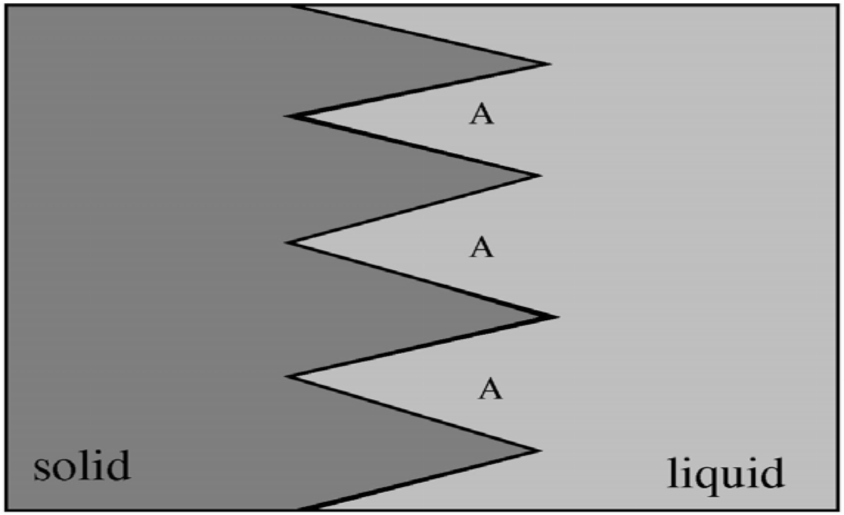
Capillarity convection



Convection

Shrinkage flow:

- comes from density variation between solid and liquid
- can lead to shrinkage cavity formation
- dominant factor of porosity formation
- source of motion
- inverse segregation



Capillarity effect

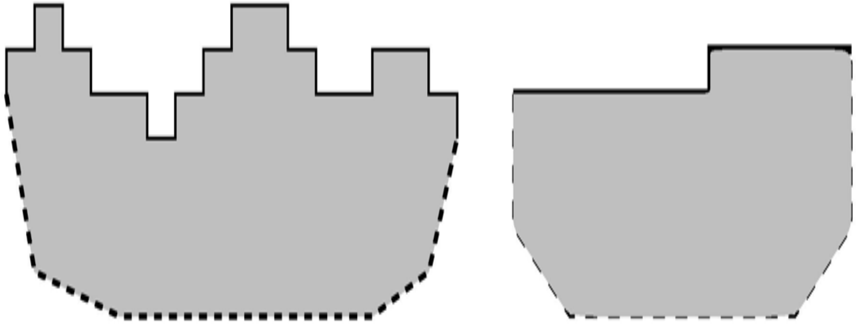
Capillarity effect:

- diffusion of solute (and/or heat) tends to minimise the scale of the morphology (maximise curvature)
- capillarity effects tends to maximise the scale (minimise curvature)

$$\Delta T_r = \Gamma\kappa, \qquad \kappa = \frac{1}{r_1} + \frac{1}{r_2}, \qquad \Gamma = \frac{\sigma}{\Delta S_f}$$

Attachment to the interface

- diffuse interface
- flat interface



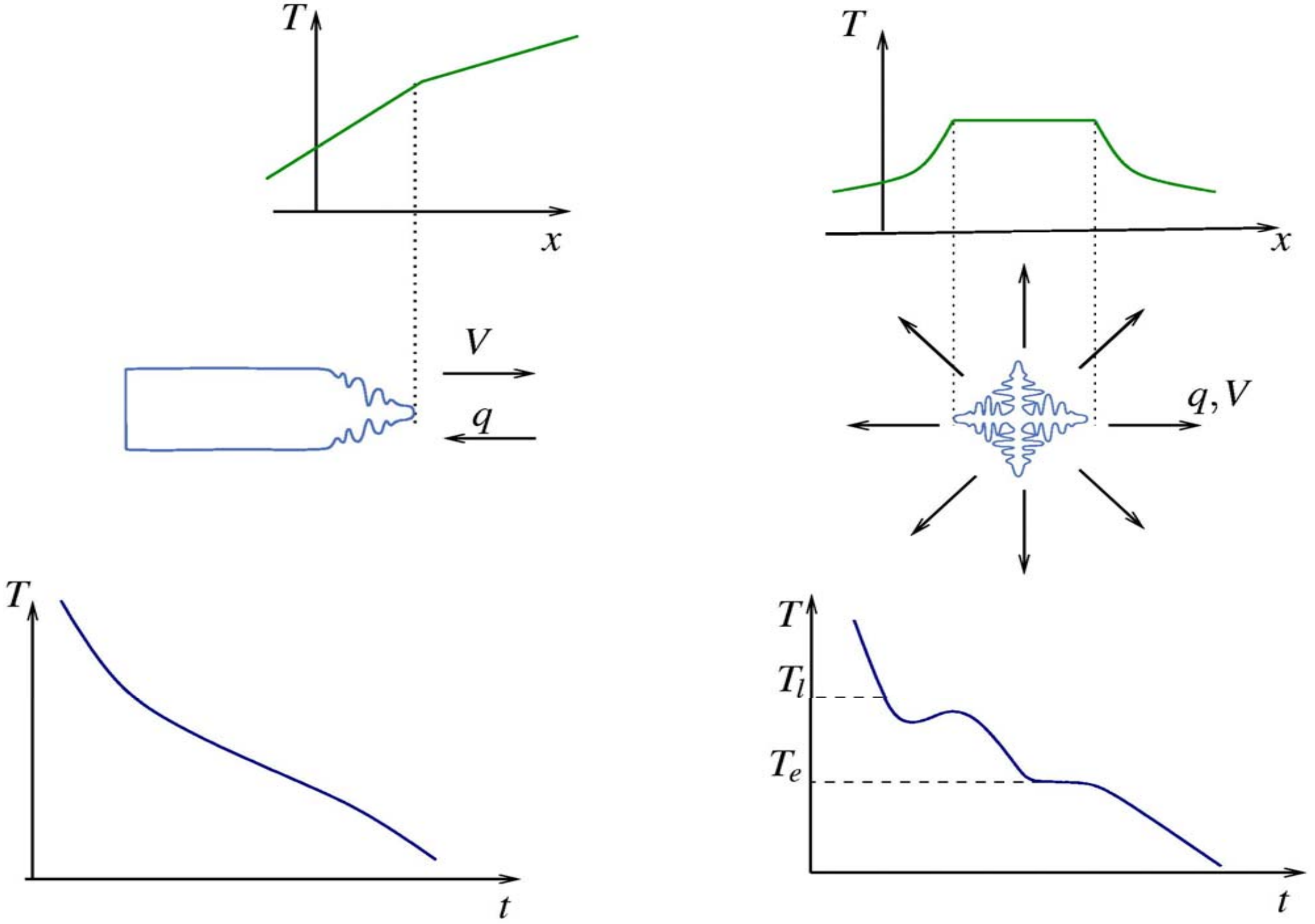
Material	$\alpha = \frac{\Delta S_f}{R}$	morphology
regular materials and some organics	< 2	non-faceted
semi-metals and semiconductors	$2.2 \div 3.2$	faceted
most organics	> 3.5	faceted

Dendritic and eutectic growth

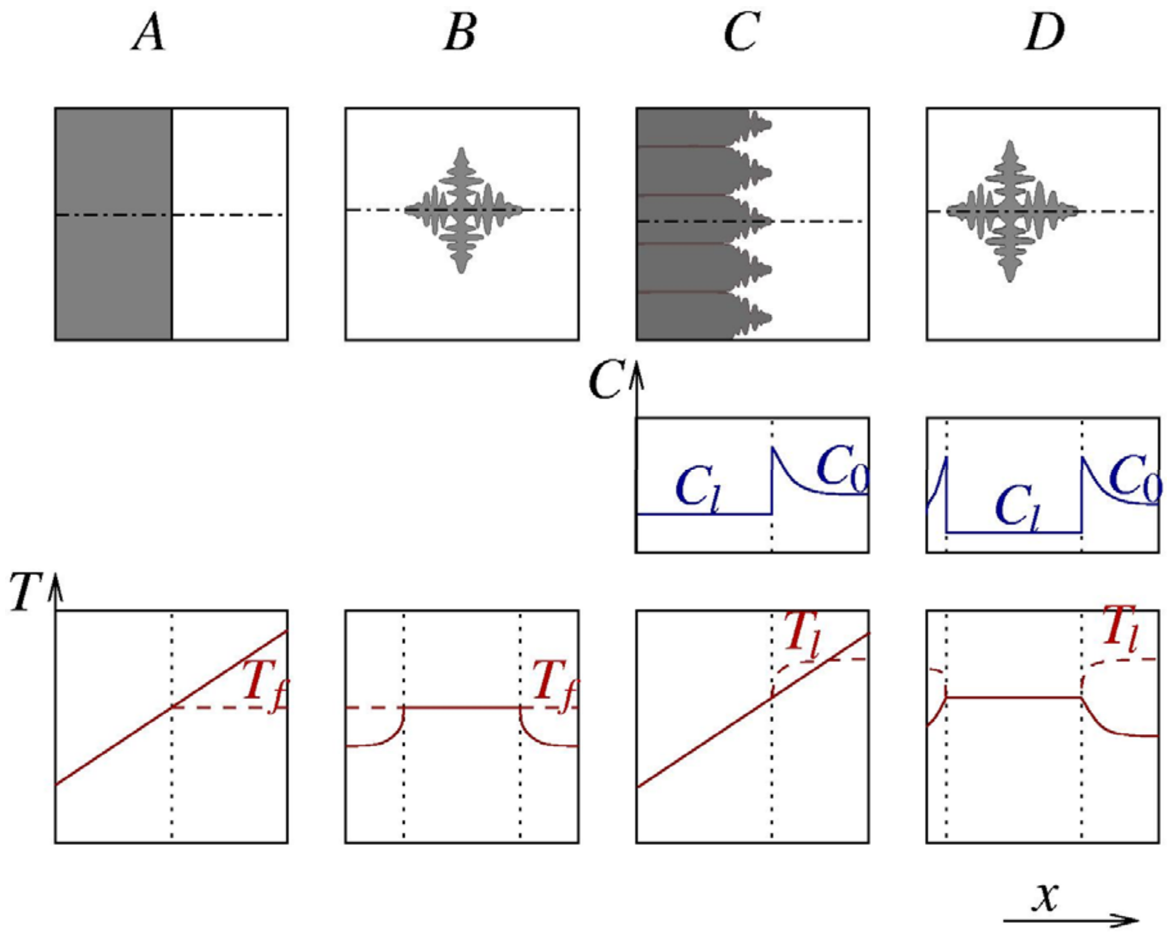
Dendritic growth

- equiaxed dendrites of pure substances
- equiaxed dendrites of alloys
- columnar alloy dendrites

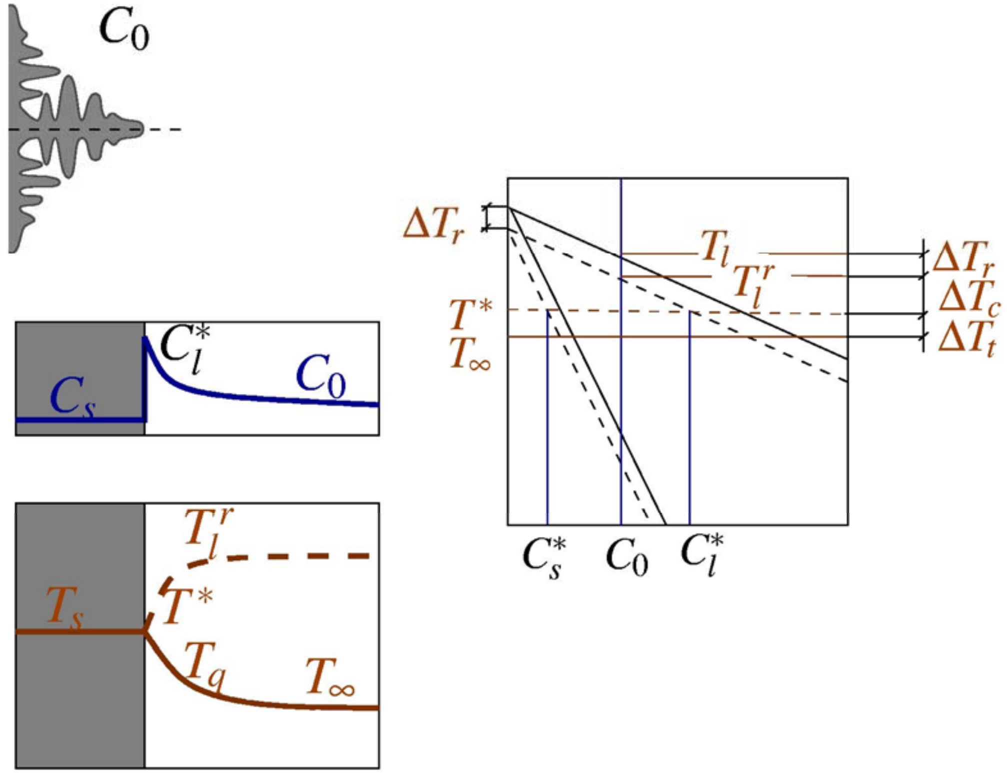
Dendritic growth



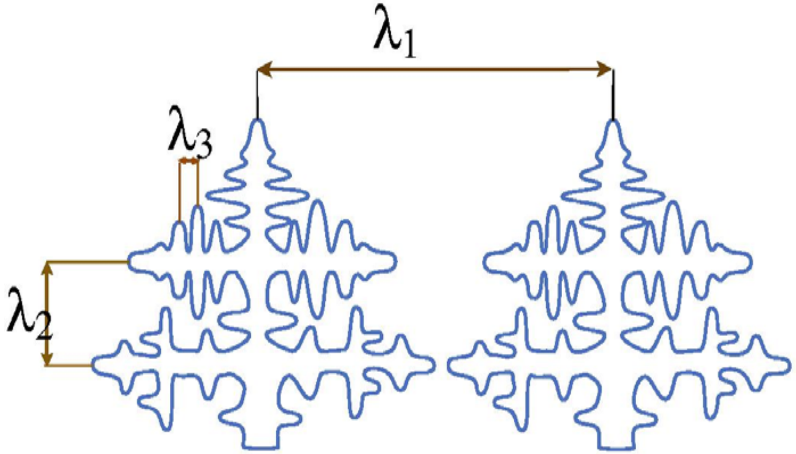
Dendritic growth

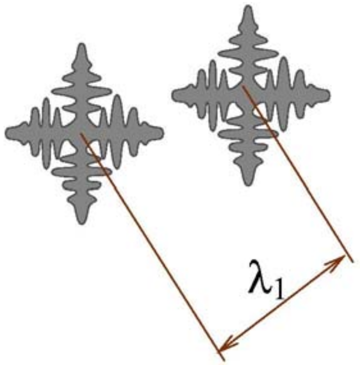


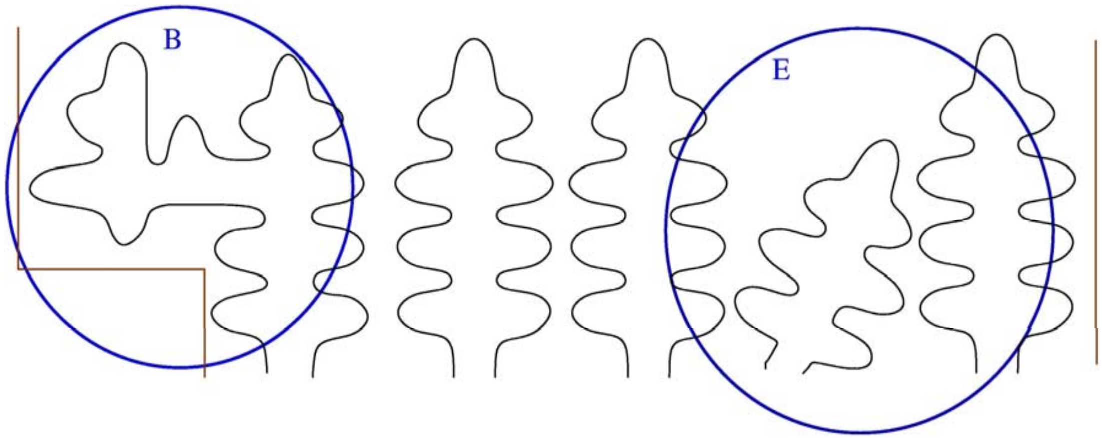
Dendritic growth



Dendritic growth







Dendritic growth

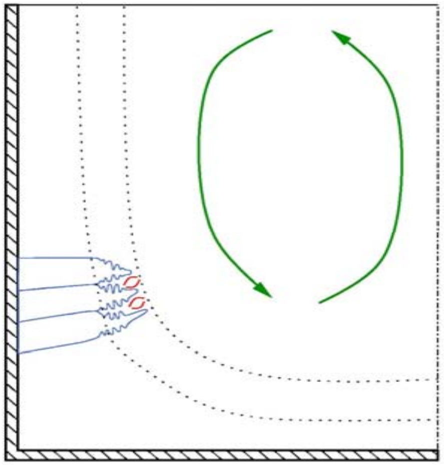
Direction of dendrites

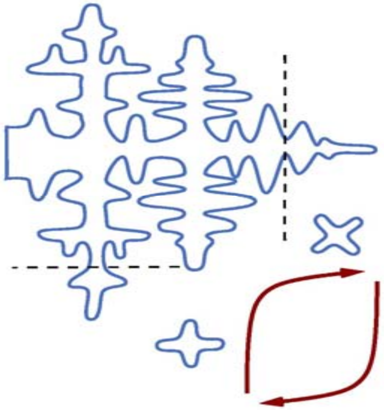
Structure	Dendritic growth
Face-centred cubic	$< 100 >$
Body-centred cubic	$< 100 >$
Hexagonal close-packed	$< 10\bar{1}0 >$
Body-centred hexagonal	$< 110 >$

Dendritic growth

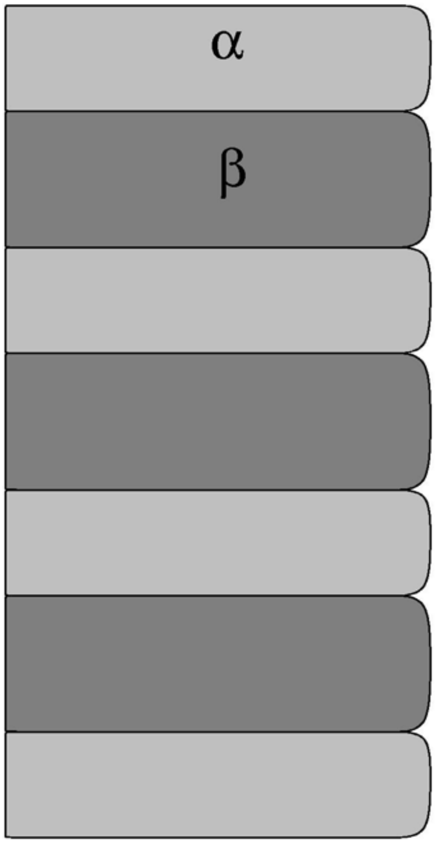
Role of convection in the liquid phase:

- decrease diffusional layer
- change of the concentration
- dendrite bending and orientation change
- dendritic arm detachment
- flow of crystal





Eutectic growth



$$l \rightarrow \alpha + \beta$$

Compositions of α and β phases (phase diagram)
size and arrangement of the layers (kinetics)

Eutectic growth

Classification in respect to the phase geometry:

- regular eutectic
- irregular eutectic
- complex regular quasi regular
- broken lamellar
- spiral
- Globular

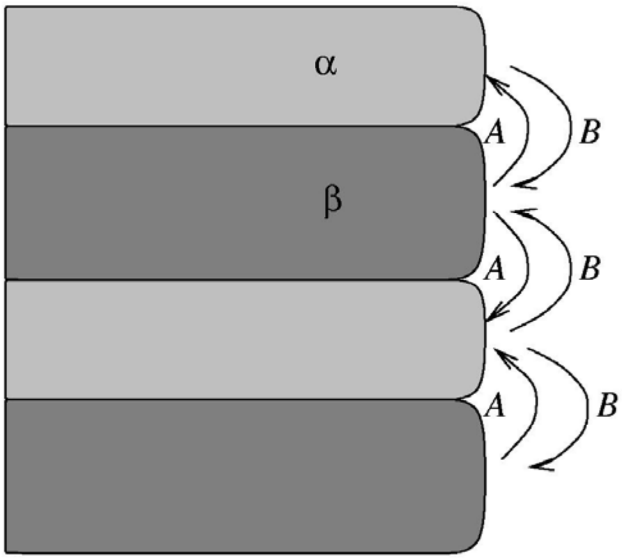
Classification in respect to the phase kinetics:

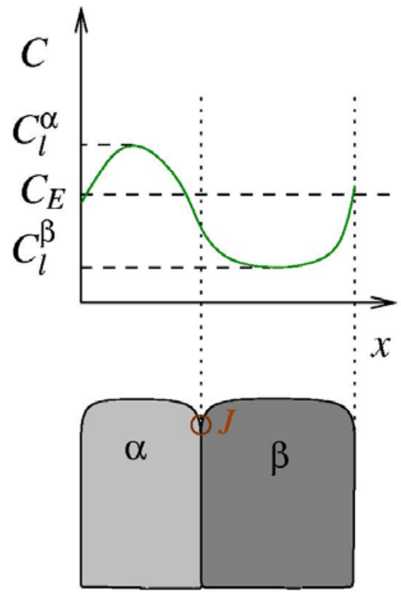
- non-faceted / non-faceted eutectic
- non-faceted / faceted eutectic
- faceted / faceted

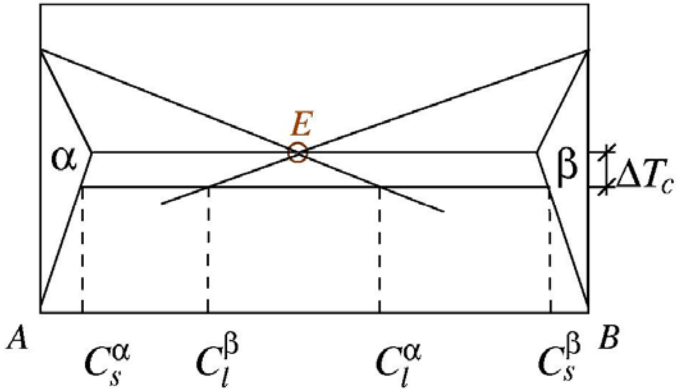
Classification in respect to the growth mechanism:

- cooperative growth of two phases
- divorced growth

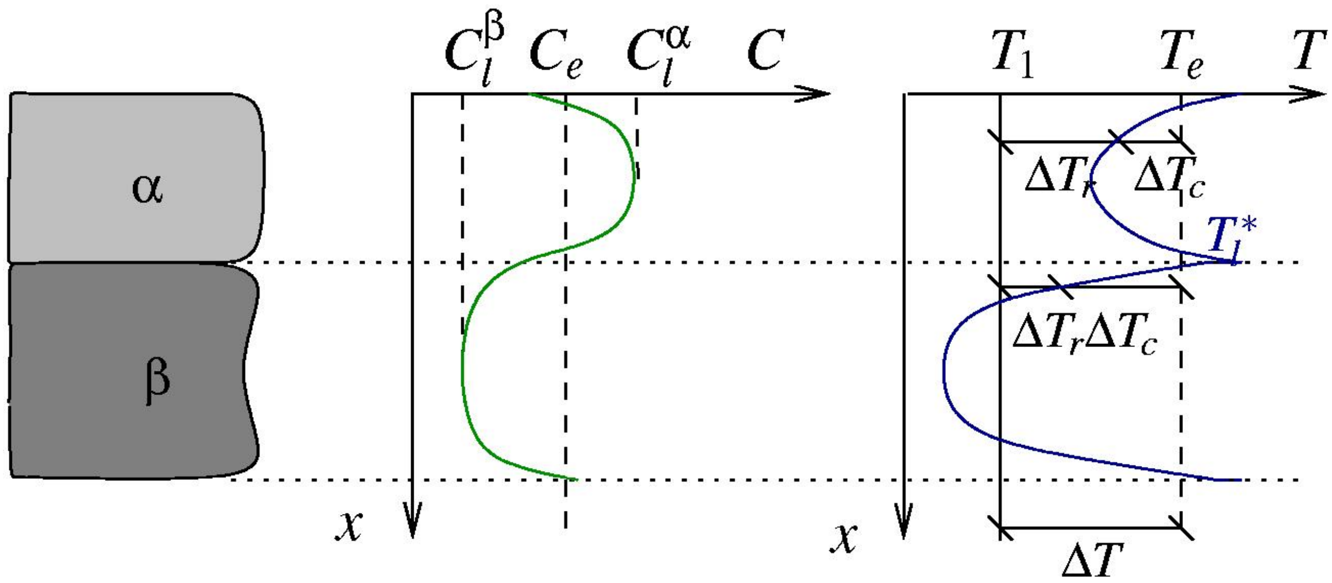
Eutectic growth



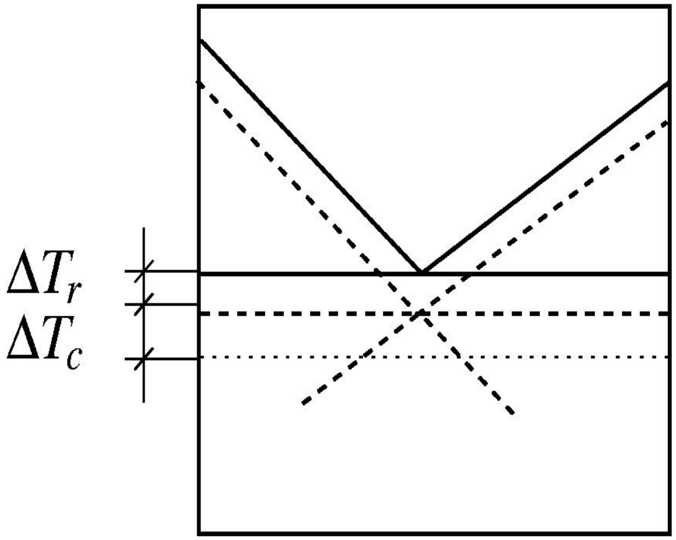




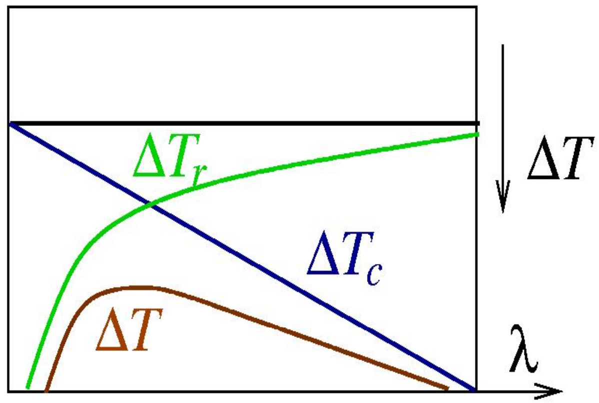
Eutectic growth

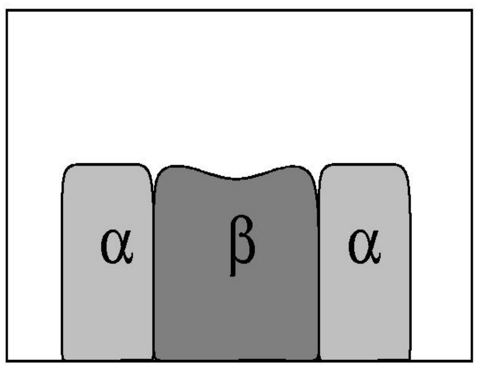


Eutectic growth



$$\Delta T = \Delta T_c + \Delta T_r$$



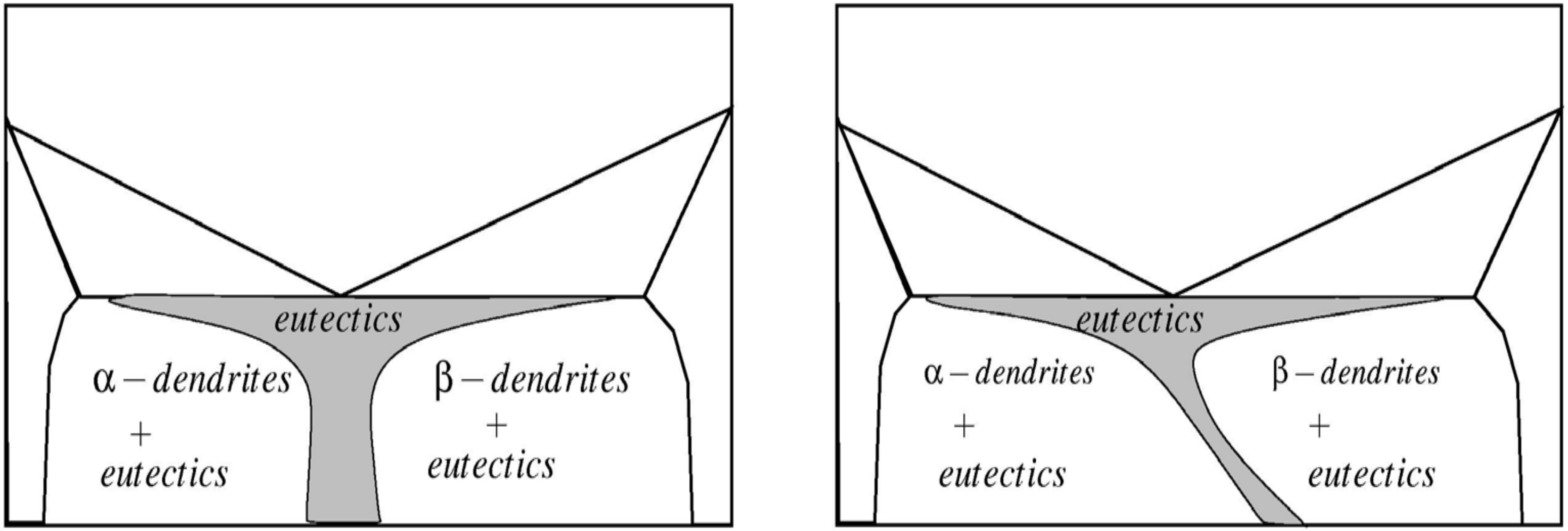


Eutectic growth

Competitive growth of dendrites and eutectic due to:

- one phase instabilities
- two phase instabilities

Eutectic growth



Interaction between phases and grains

(formation of the alloy microstructure)

Microstructure formation

Fee dendritic growth

- interdendritic flow,
- crystal can move

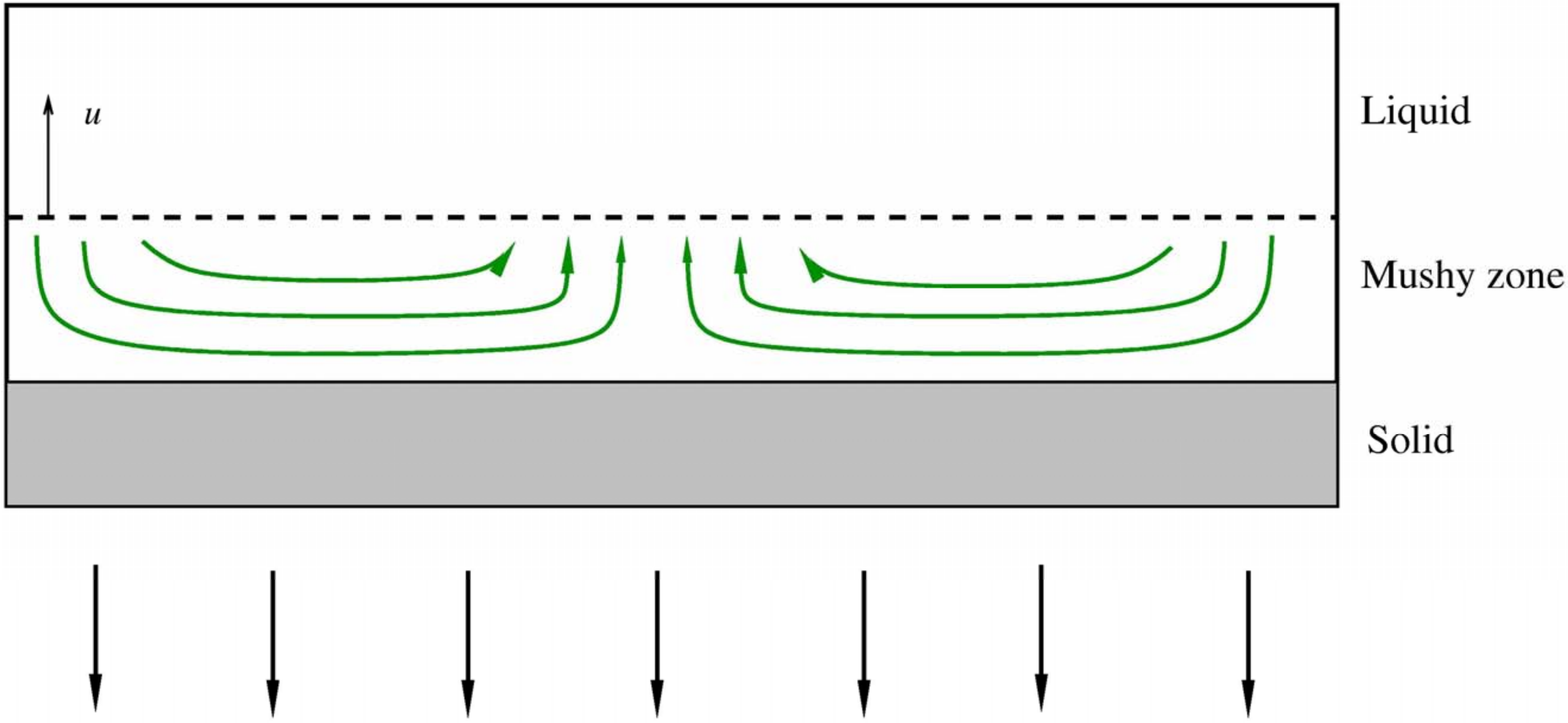
Reaching coherency point

- Coherency point is cooling rate, equiaxed grain size and concentration dependent

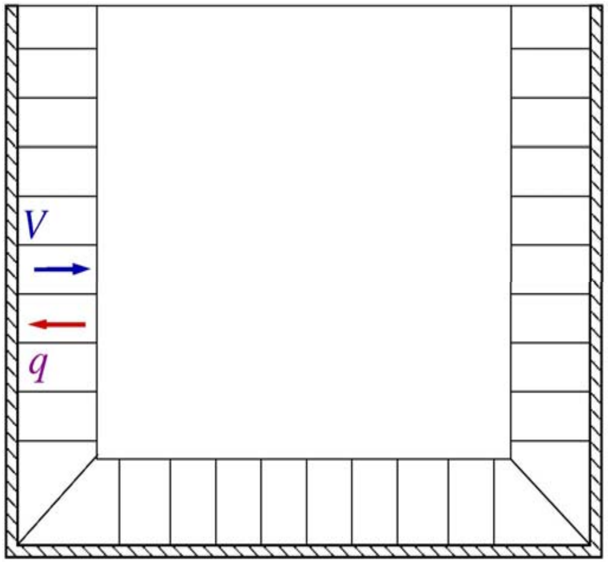
Solid skeleton form

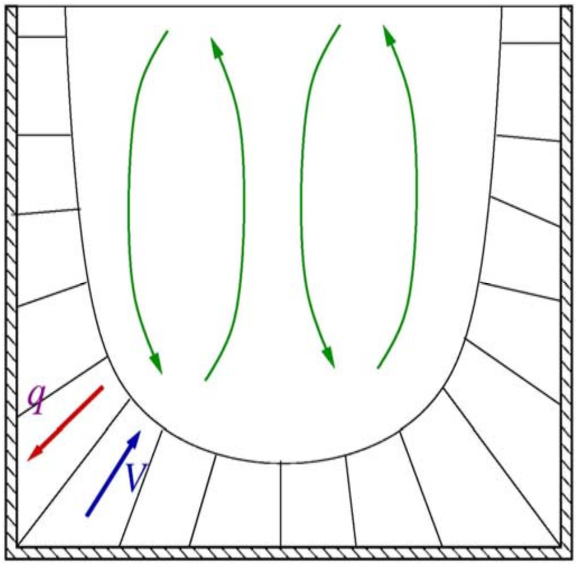
- interdendritic flow only possible
- stress development

Microstructure formation

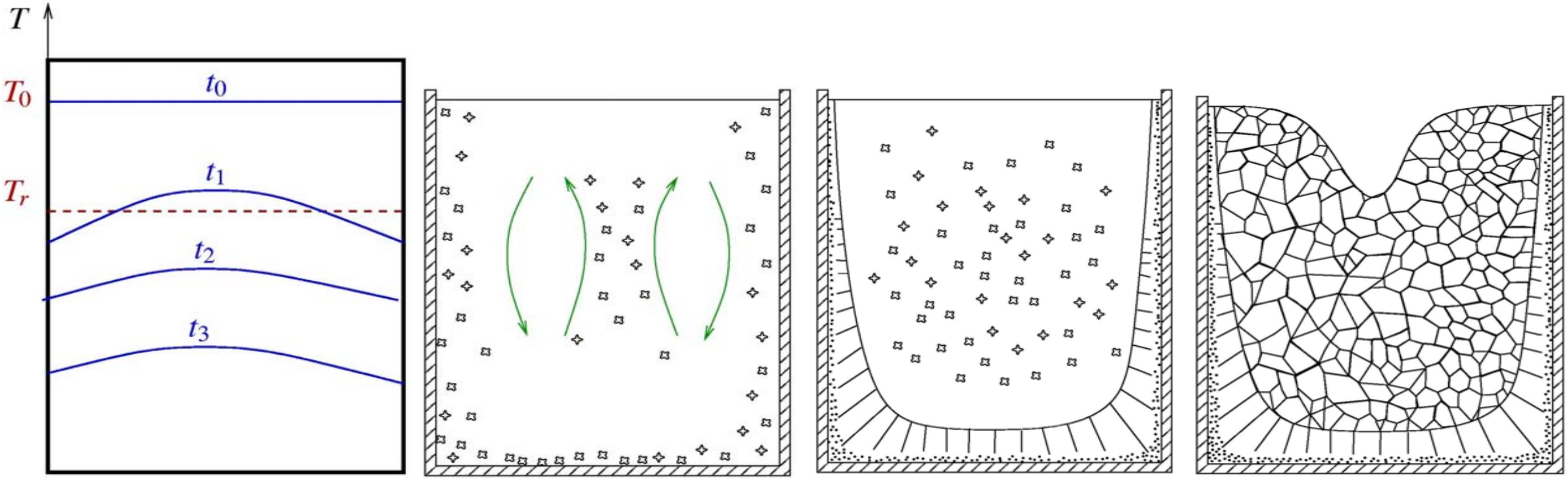


Microstructure formation





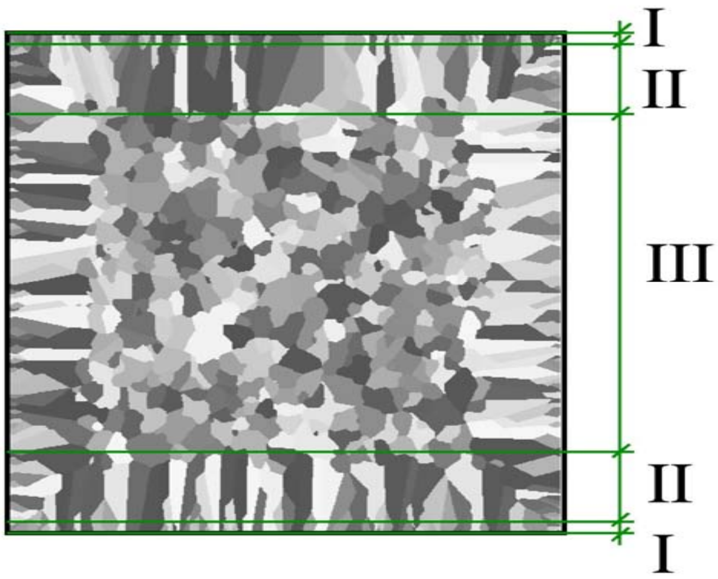
Microstructure formation



Microstructure formation

Zones in as-cast:

I. fine zone
II. columnar zone
III. inner equiaxed grains zone



Microstructure formation CET

Source of the nuclei in the bulk:

- constitutional undercooling driven nucleation
- big bang mechanism
- dendrite detachment mechanism

Microstructure formation
CET

Competition between equiaxed and columnar growth:

- degree and extend of constitutional undercooling
- columnar front velocity
- dendrite detachment mechanism
- convection and stirring in liquid phase

Single crystal growth

Motivation for such studies:

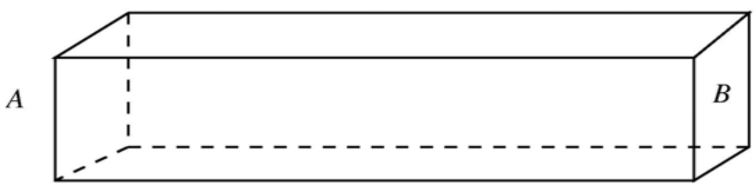
- research – better understanding of the process and study of the properties
- real-life applications – turbine blade

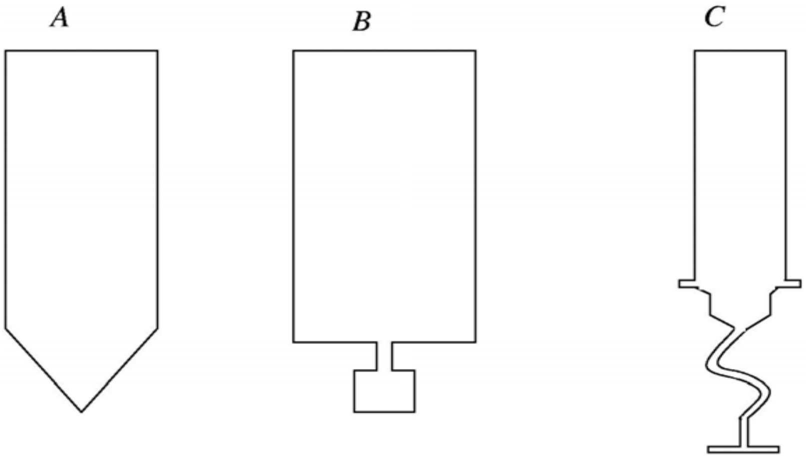
Control of such parameters, like:

- orientation
- shape
- concentration
- perfection

Single crystal growth

Control of orientation

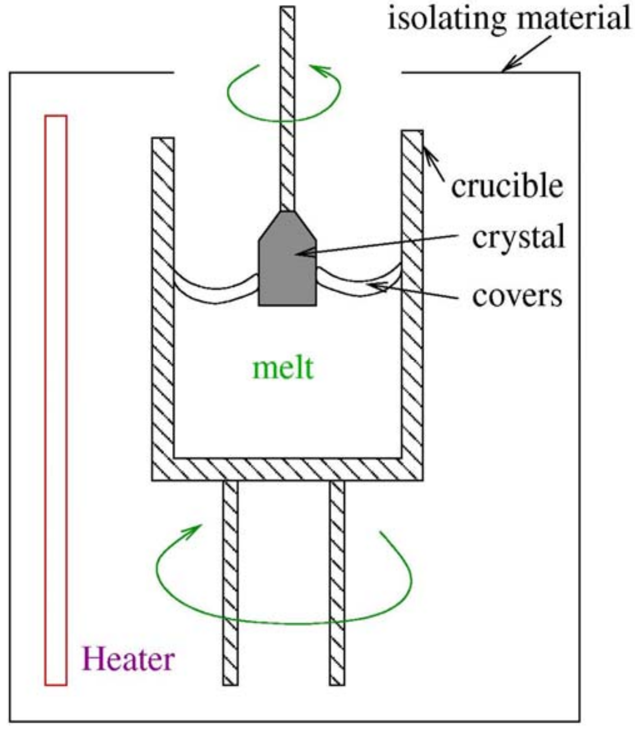


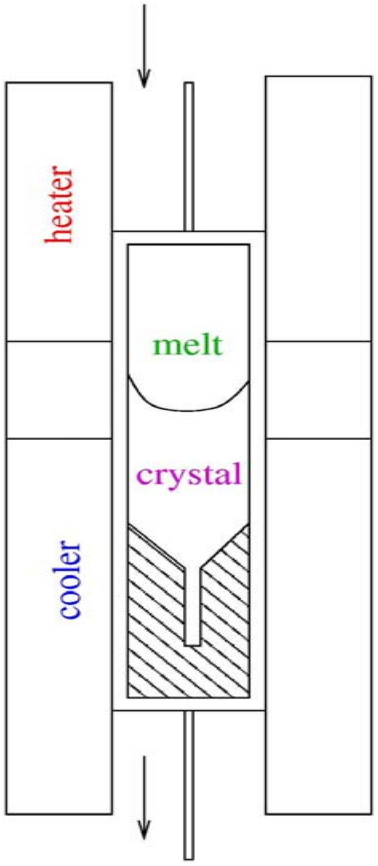


Single crystal growth

Methods of the shape control:

- Bridgman method
- Czochralski method
- others

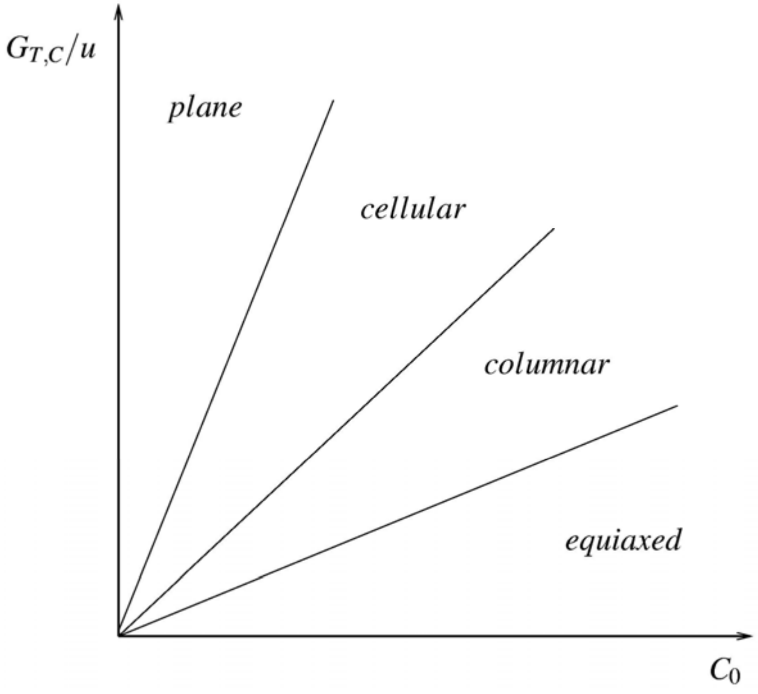




Single crystal growth

Control of concentration:

- contamination
- evaporation
- uniformity of concentration



Single crystal growth

Control of perfection:

- vacancies
- dislocations
- substructures

Summary - convection

Causes:

- external (magnetic field)
- internal (concentration and temperature dependent density variation, surface tension variation, shrinkage flow)

Effects:

- diffusional layer and concentration variation
- micro and macrosegregation
- chimney effect - “fracles”
- macroscale columnar interface shape changes
- dendrite arm detachment and flow of the crystal
- promotes the CET

Keypoints - 1

- crystallisation is associated with the discontinuous increase in viscosity
- microstructure defines phases and morphologies
- microstructure depend not only on thermodynamic but also on kinetic of transition
- the kinetics of atom attachment to the interface, capillarity, diffusion of heat and mass, natural and forces convection, time scale affect the crystal growth

Keypoints - 2

- diffusion and convection as a mechanism of transport process
- diffusion tries to bring the system into equilibrium
- convection-a current motion which results in th mixing of the fluid
- external and internal driving forces for convection
- capillarity effect tends to maximise the scale of morphology
- diffusion tends to minimise the scale of morphology
- attachment kinetics leads to diffuse and flat types of interface

Keypoints - 3

- columnar dendrites are constrained by the positive temperature gradient, equiaxed dendrites grow in the liquid of negative gradient
- microstructure is characterized by different-order spacing
- interdendritic flow changes diffusional layer; dendrites bending, arm detachment and flow of crystal is observed
- eutectics consists of two phases
- diffusion tends to decrease the lamellar spacing, and curvature effect tends to increase the spacing.
- instabilities cause competitive growth of dendrites and eutectics
- symmetric or assymetric coupled zone can be observed

Keypoints - 4

- free growth is observed before reaching the coherency point
- when solid skeleton is formed stresses may develops
- mushy zone - region where solid and liquid phase coexist
- chimney effect can be observed within the mushy zone
- convection can also affect the macroscopic columnar interface
- typical as-cast microstructure consists of three zones
- CET - result of competitive growth between equiaxed and columnar crystals
- quality of monostructure depends on the control of orientation, shape, concentration, and perfection.

References

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