MME 345

Lecture **B:05**

Solidification and Crystallisation

4. Formation of dendrites

Ref:

[1] A. Ohno, The Solidification of Metals, Chijin Shokan Co. Ltd., 1976

[2] J. Campbell, Castings, Butterworth-Heinemann, 1991

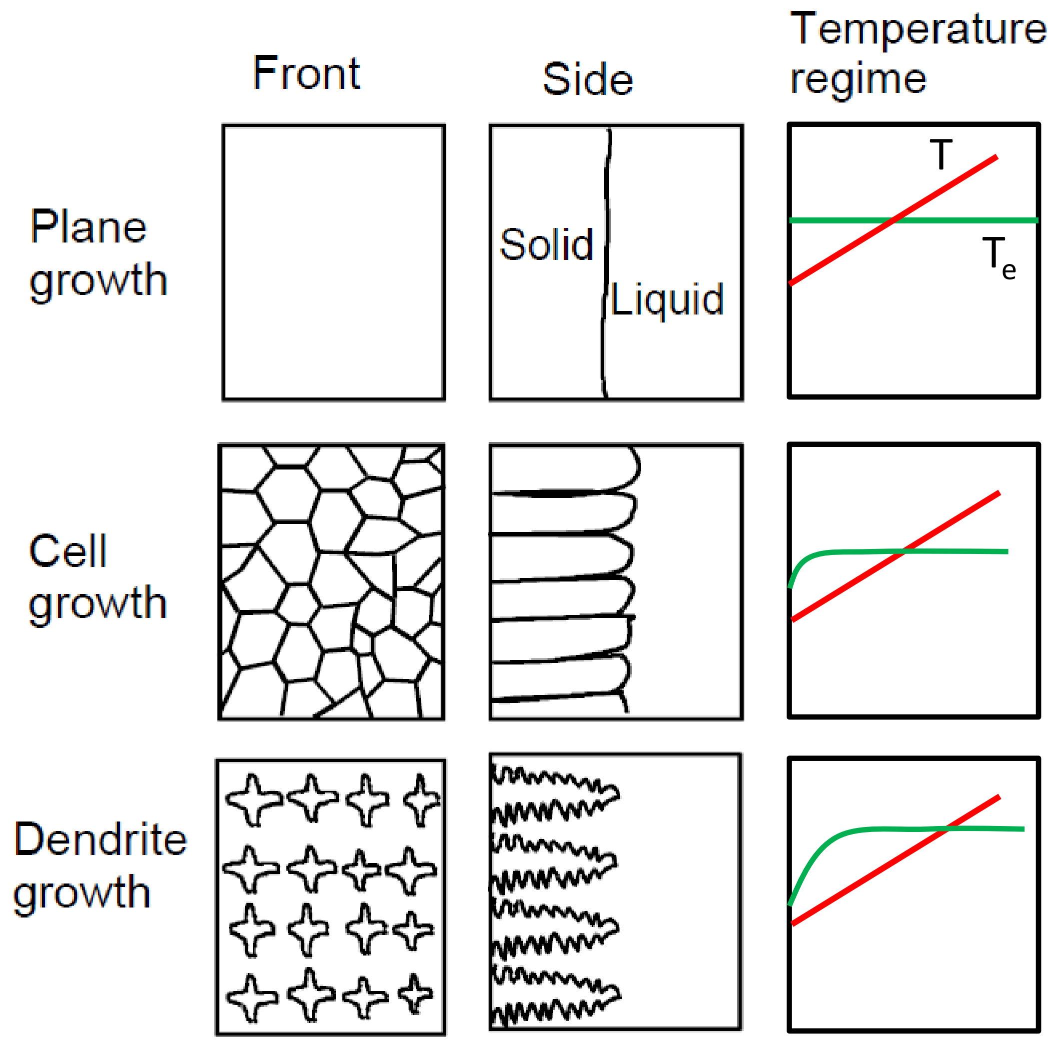
Topics to discuss today ….

1. Mechanism of dendrite formation
2. Dendrite arm spacing (DAS)

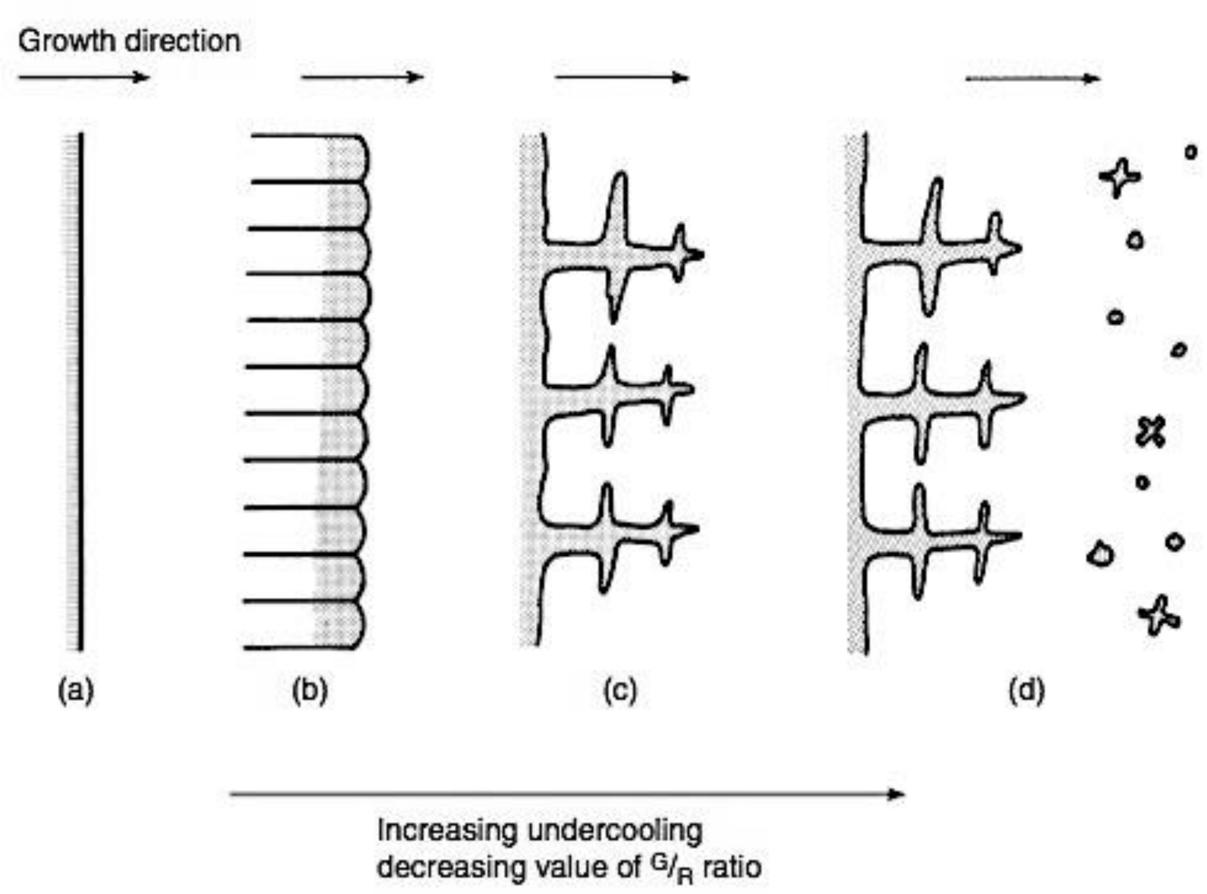
Review of earlier class

Transition in Growth Morphology

- The growth morphology changes from planar to cellular and then to dendritic as the compositional depression of undercooling increases.
- Although metals can solidify in any of these modes, the most common form in real castings is dendritic solidification.
- A dendrite can be defined as the basic tree-like growth form of the solidification front which occurs when instability predicted by the compositional depression of undercooling condition is high.



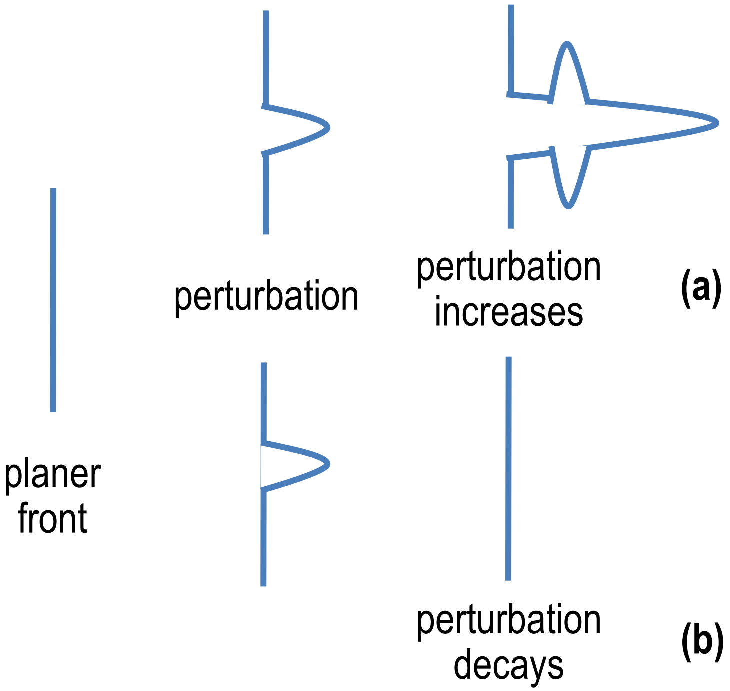
The growth morphology changes from planar to cellular, to dendritic as the compositional depression of undercooling increases (equivalent to G/R reducing)



influence of undercooling on interface morphology and mode of growth.
(a) planar interface, (b) cellular interface, (c) dendritic growth, (d) independent nucleation

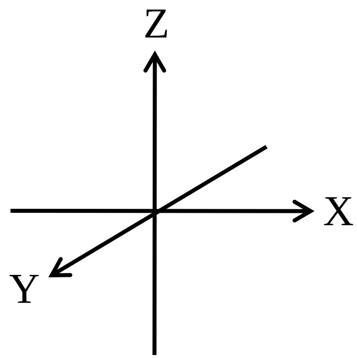
1. Mechanism of formation of dendrite

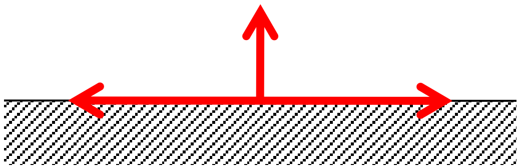
- For most commercial casting alloys forming solid solutions, dendritic structures were observed because of faster cooling rate and high solute segregation.
- Any perturbation developed on the solid face due to high undercooling tends to become stable and act as a centre for preferential growth.
- As the solute segregation increases, the tips of certain axes, where the segregation is the smallest, start to project forming the main axes of dendrite.



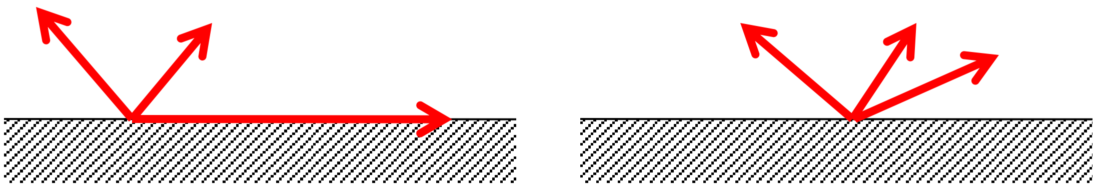
interface instability :
(a) stable, (b) unstable

- All three main axes of crystals growing inside the liquid will grow at the same rate.





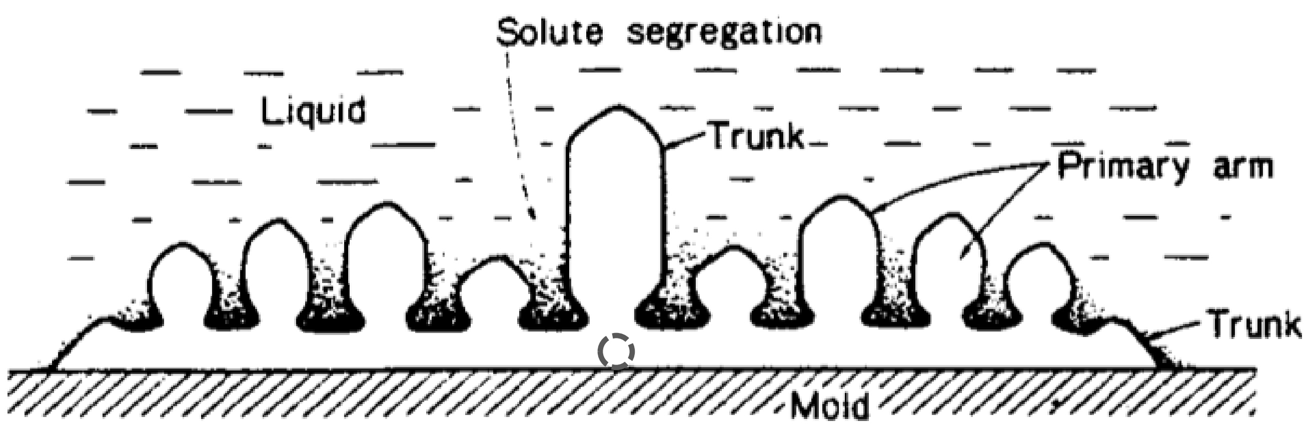
- If a crystal nucleates on the mould wall, the main axes and their arms of a dendrite do not grow equally in all directions.



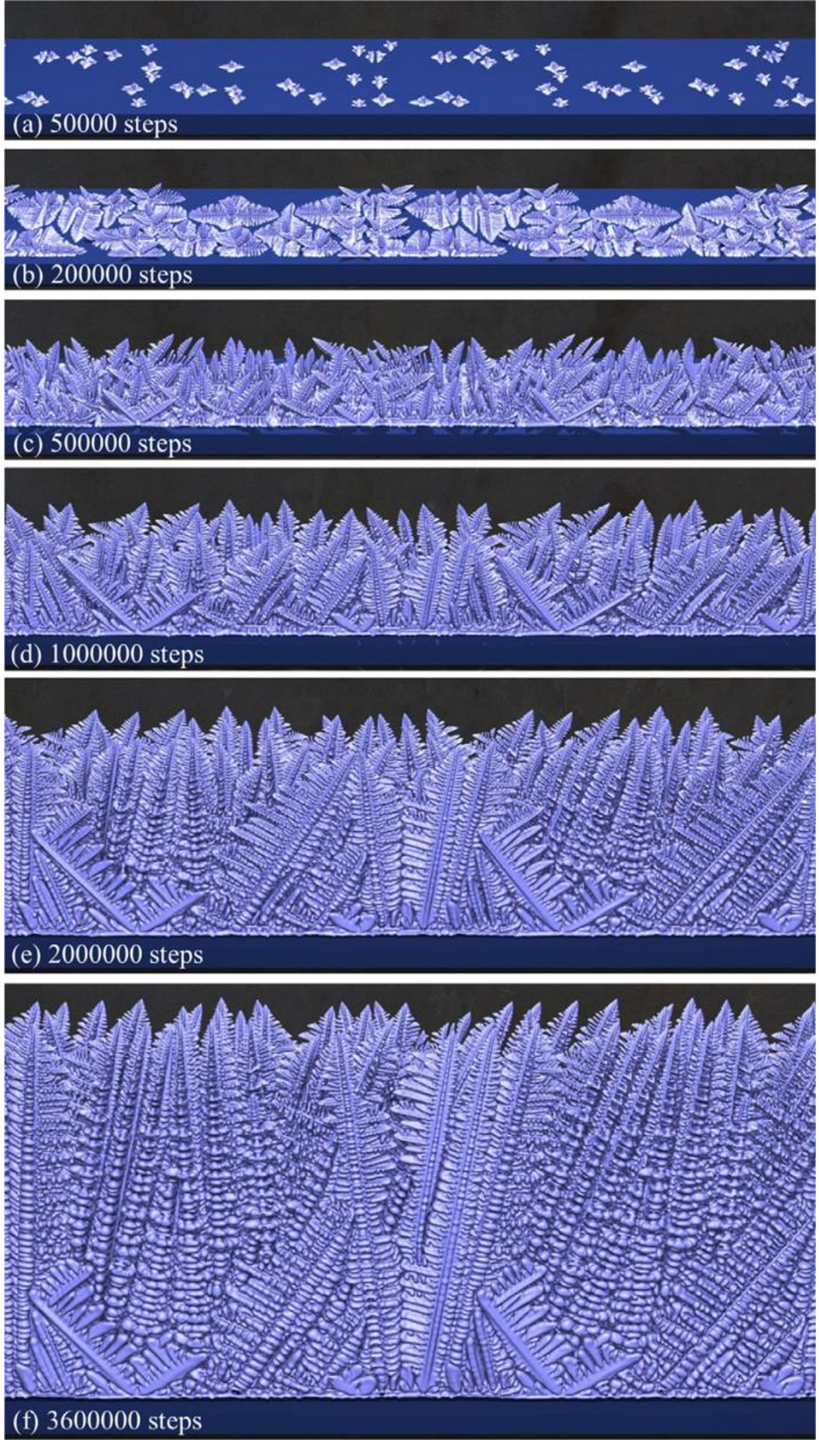
mould surface and the growth direction of dendrite main axis

- Since the undercooling in the liquid is the largest at the mould wall, axes growing along the mould wall will grow at a much faster rate than the axes growing away from the mould wall.

- Dendrites normally grow from a single nucleus which may be only a few μm in diameter.
- The nucleus may be a foreign particle or a fragment of another grain. The dendrite grows both forwards and sideways.
- Primary arms which grow upward and parallel to the main axis (or trunk) on each of the main axes which lie on the mould wall.

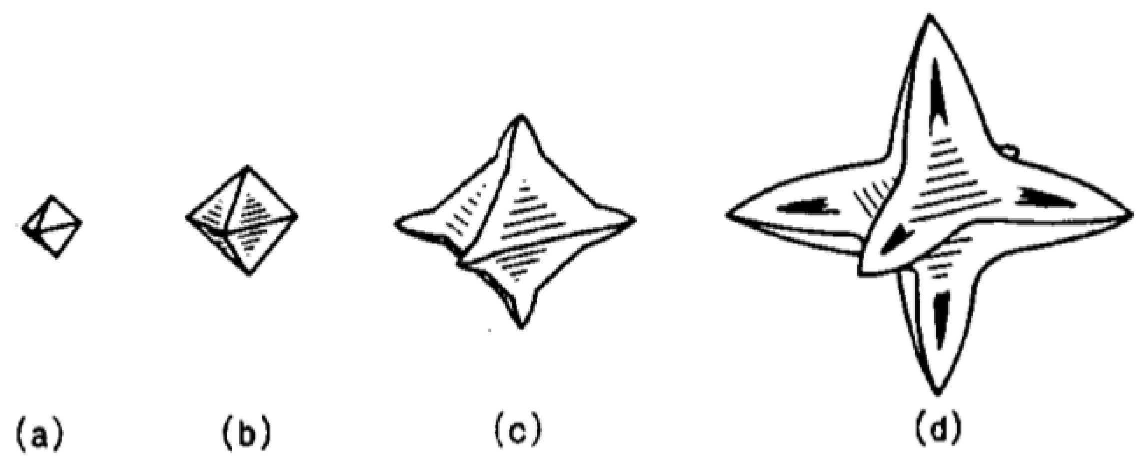


growth of dendrite arms on the mould wall in the initial stage of solidification

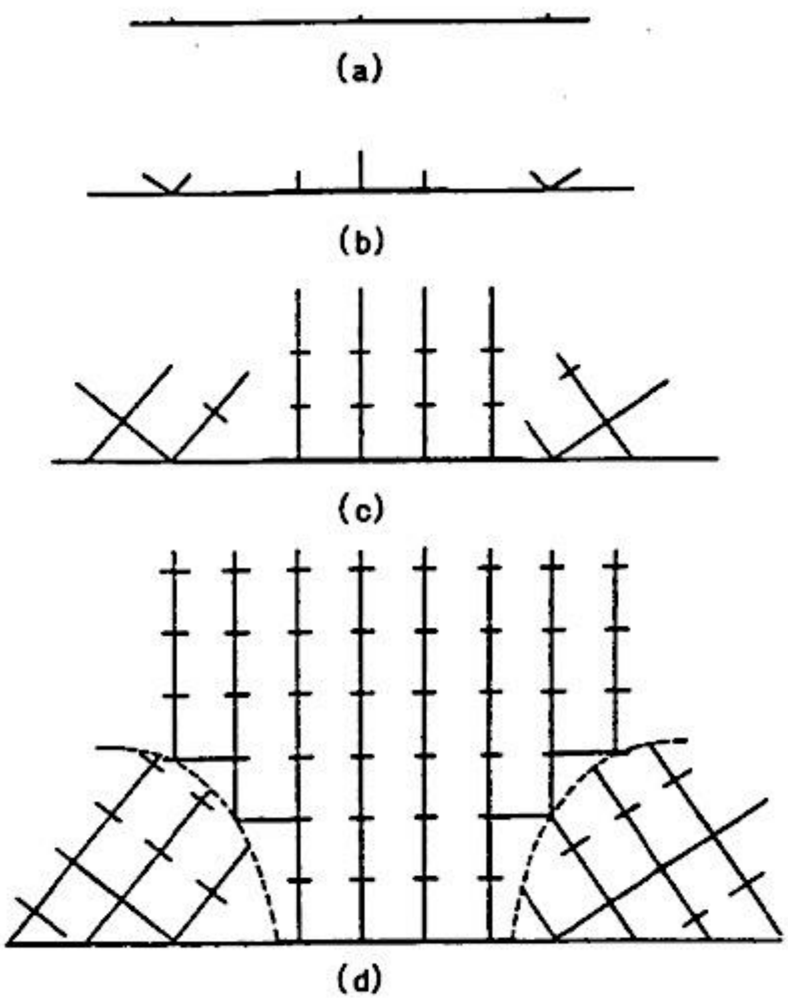

(a) 50000 steps
(b) 200000 steps
(c) 500000 steps
(d) 1000000 steps
(e) 2000000 steps
(f) 3600000 steps

- When a small free crystal of aluminium grows in octahedron shape in the liquid, it maintains its external shape until solute segregation prevent its uniform growth.

- As solute segregation at the base increases, the tips of the six pyramids, where solute segregation is expected to be the smallest (and undercooling is the largest), progress preferentially and start forming the main axes of dendrite.



formation process of the dendrite main axis from an octahedron shaped crystal



schematic diagram showing crystal growth from the mould wall

- Generally the dendrite arms which are preferentially growing are called the primary dendrite arms.
- In actual cases, a dendrite consists of the main axes, the primary arms, the secondary arms, and even the tertiary arms.
- Although the arms grow in different physical directions, they all have the same crystallographic structure and orientation, i.e. a dendrite is a single crystal.

- So far we have shown that, dendritic growth is occurred unidirectionally from a major interface (mould wall, etc.), which would produce columnar-dendritic grains

- But dendritic growth may also equally be associated with a crystal growing independently within the melt.

- In this case the growth interface is the whole periphery of the crystal and the fully developed grain is approximately equiaxed.

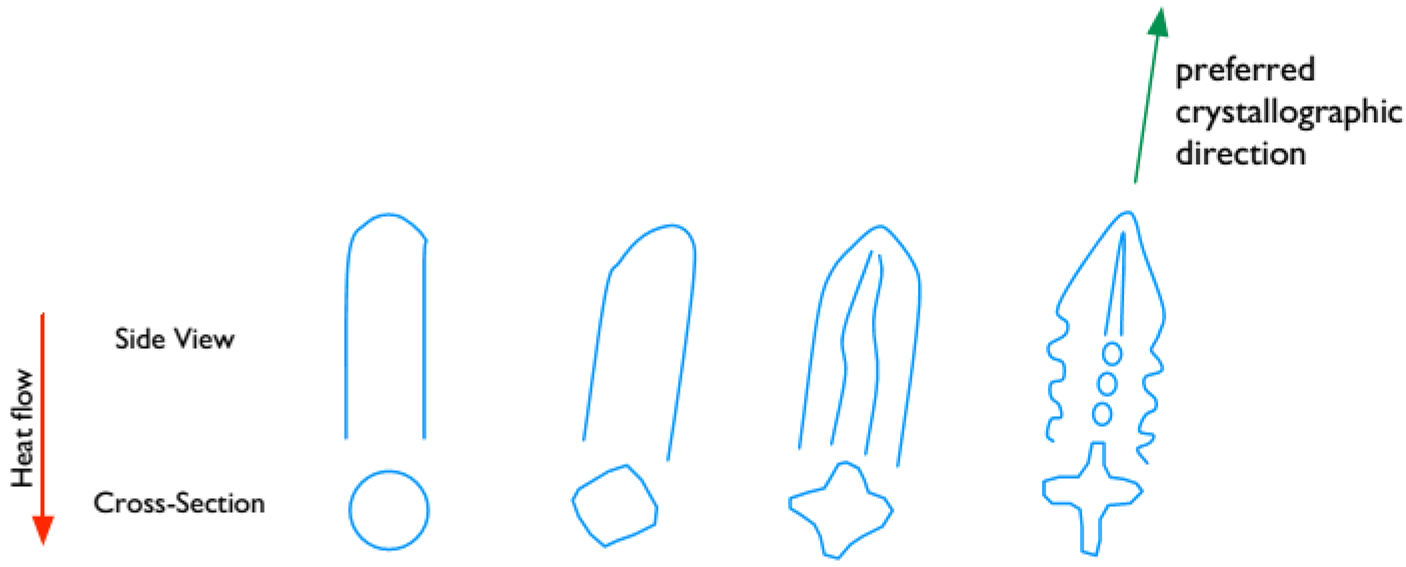
1.1 Growth of dendrites

- Dendritic growth is strongly crystallographic.

- Small misorientation can be produced during growth by mechanical distortions brought about by turbulence.

Metals	Structure	Preferred Orientation
Iron, β-Brass	bcc	<100>
Aluminium, Copper, Lead	fcc	<100>
Zinc	hcp	<1010>
Tin	bct	<110>

- When regular cells form and grow at relatively low rates, they grow perpendicular to the liquid-solid interface regardless of crystal orientation.

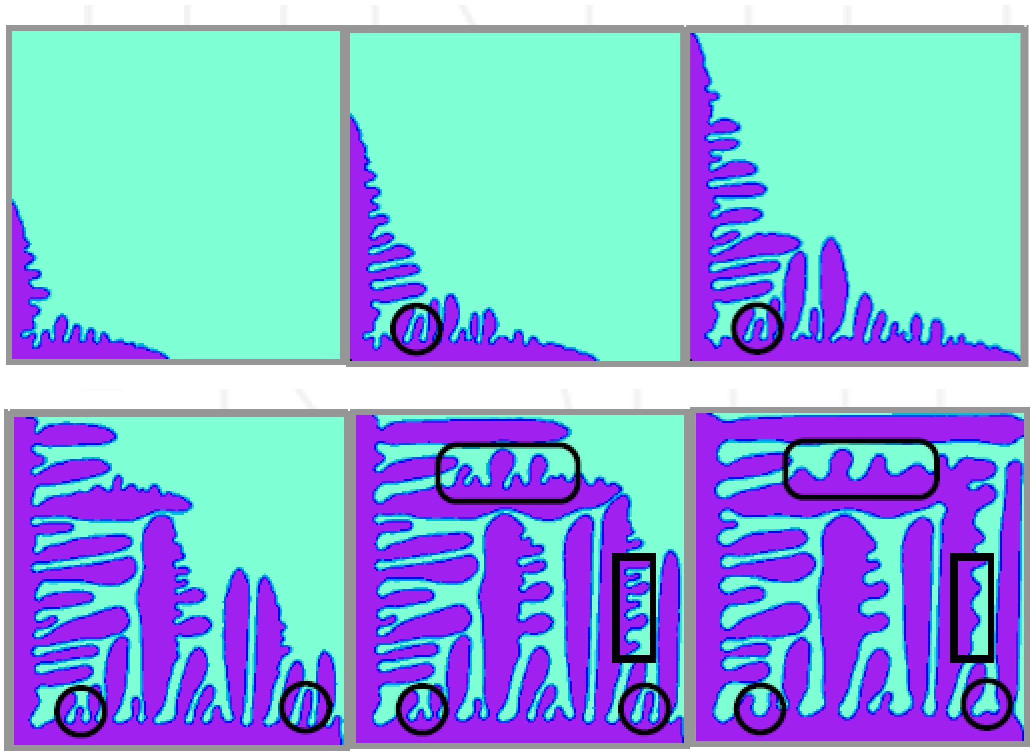


- When the growth rate is increased, crystallography effects begin to exert influence and the cell growth direction deviates toward the preferred crystallographic growth direction.

- Simultaneously, the cross section of the cell generally beings to deviate from its previously circular geometry owing to the effects of crystallography.

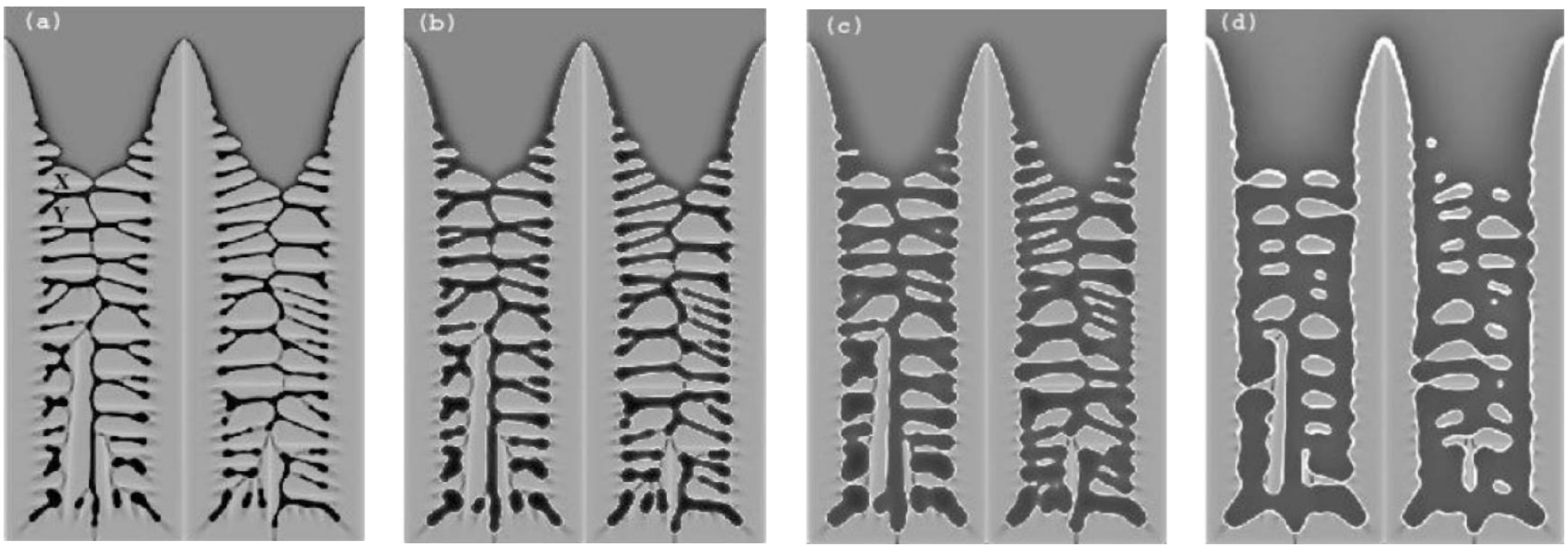
- In the process of dendrite growth, some of the arms that form initially become unstable, later **remelted** while the others continue to grow.

- The secondary arms are sometimes eliminated by their neighbours, and a number of them grow perpendicularly to the primary arm.

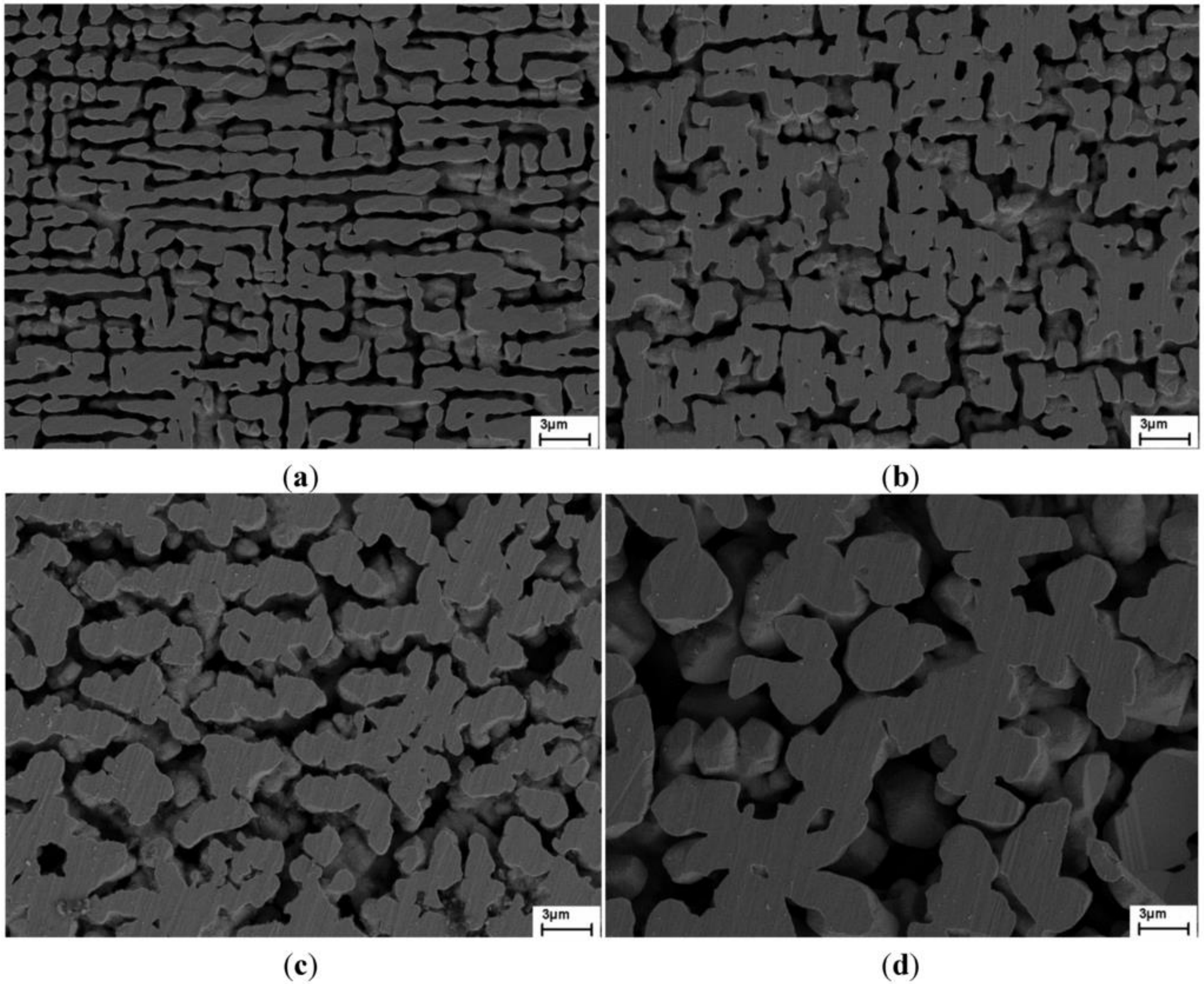


- The dendrite roots are thinner than the outer part because of the solute piling up at the root. When the hot melt flows into the dendritic root, the root can be **melted** and the dendrite arms **detached**.

- Dendrite arms can also be **fragmented** due to thermal/mechanical convection.

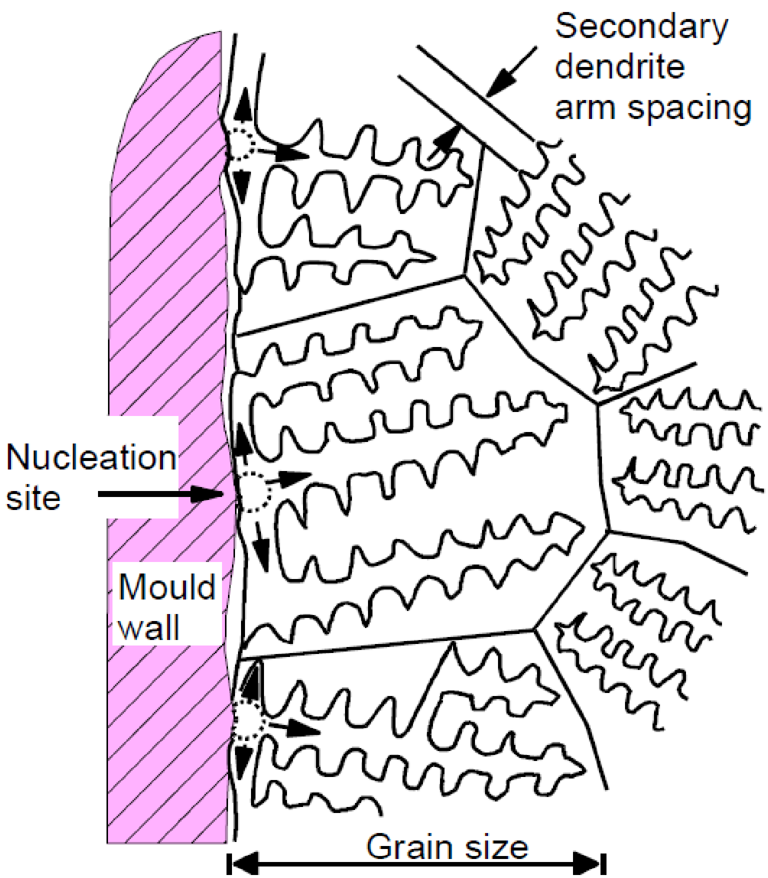


Root melting and dendrite fragments at increased temperature



Micrograph showing growth of dendrites

2. Dendrite arm spacing (DAS)



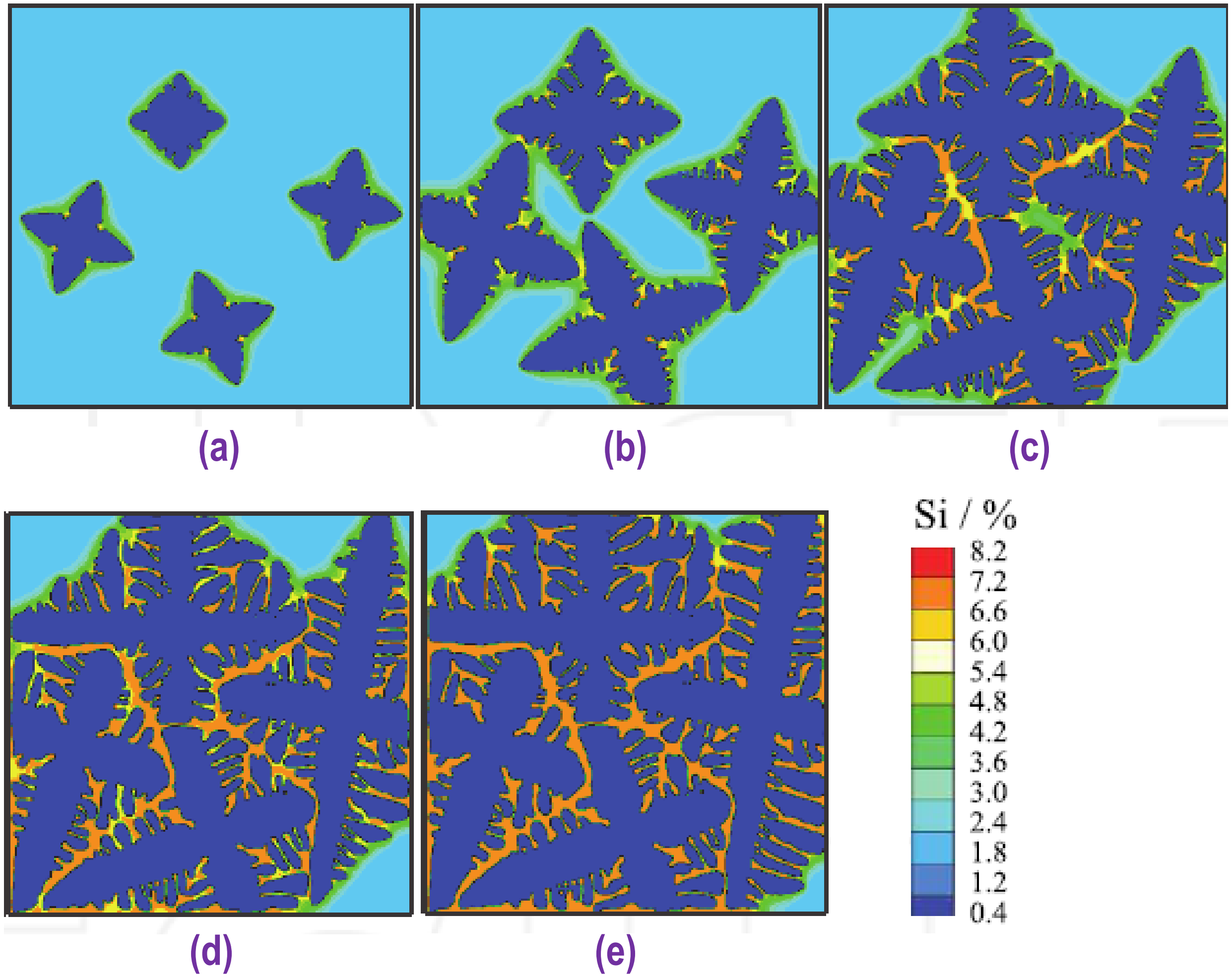
- A grain may consist of one dendrite or of a 'raft' of thousands of dendrites, but all must have the same crystallographic orientation and will have grown from the same nucleation site.
- A grain boundary is formed where rafts of different orientation meet.
- Although grain size is used to characterise the scale of the microstructure of wrought alloys, it is often more appropriate to characterise the scale of cast microstructures by measuring the 'dendrite arm spacing', or **DAS**.

Schematic illustration of the formation of a raft of dendrites to make grains. The dendrite stems within any one raft or grain are all crystallographically related to a common nucleus.

- If there is no convection or turbulence around the liquid of the main axes of dendrite, the primary, secondary and tertiary arms will form uniformly.

- The spacing between the higher-order arms is called the **dendritic arm spacing (DAS).**
  - In most cases, however, DAS refers to the spacing between the secondary arms since tertiary arms are not so prominent

- In casting, grain size is sometimes important, but more often it is the DAS that appears to be the most important structural length parameter.
  - Segregation of low-melting-point alloys and other impurities between the dendrite arms reduces the properties of the casting.
  - Thus, mechanical properties of most cast alloys are strongly dependent on the size of DAS.



Concentration profiles calculated during multi-dendrite isothermal solidification of Al-2mol%Si alloy at the temperature of 880K. The snapshots (a), (b), (c), (d) and (e) correspond to solidification time 0.04, 0.08, 0.12, 0.16 and 0.2ms respectively.

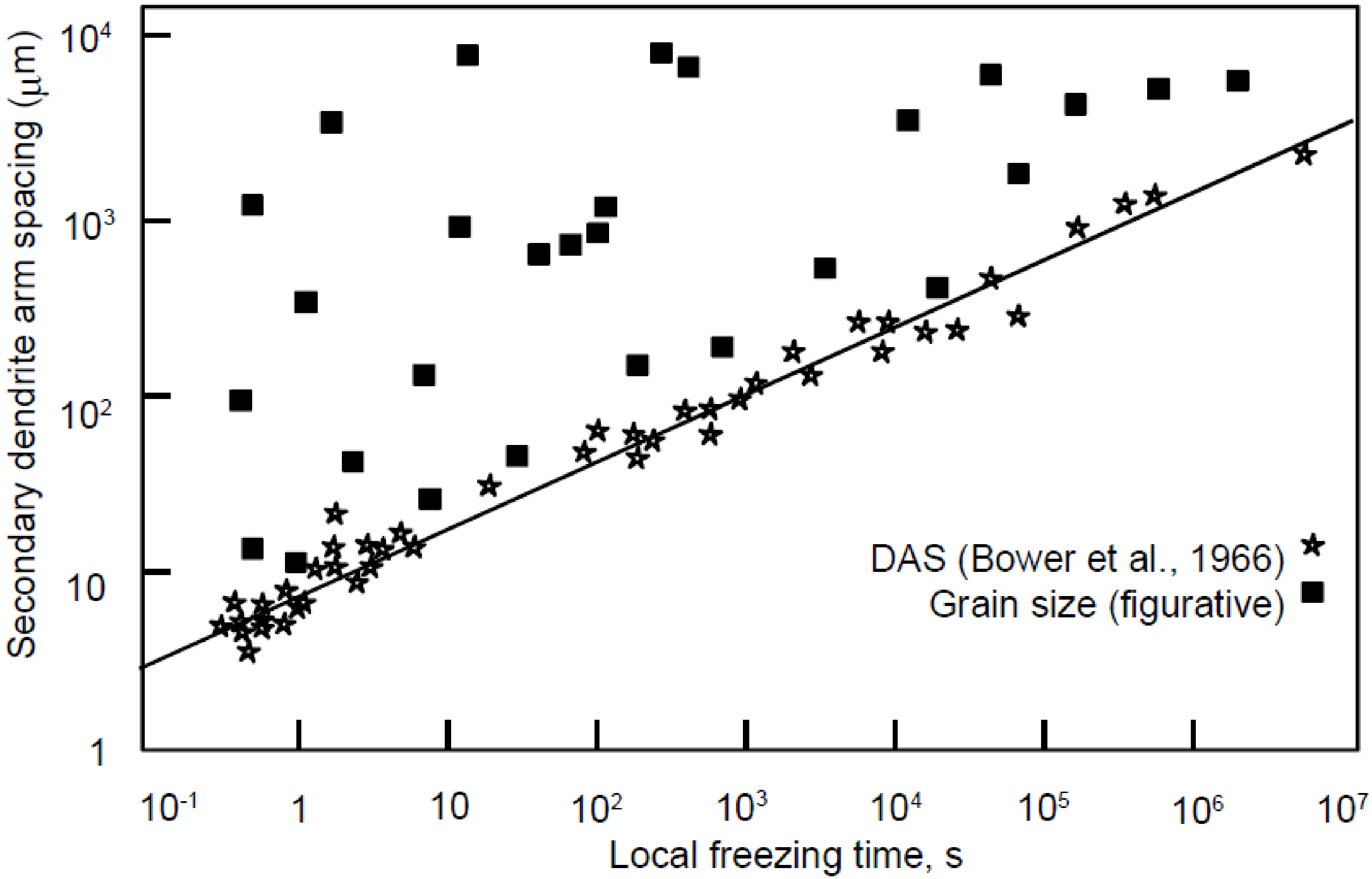
- During the growth of the dendrite, the **average DAS increases** with time as a result of coarsening, in which the driving force is the reduction in surface energy achieved by reducing the surface area.

- Some of the larger arms grow at the expense of smaller ones, leading to an increasing DAS as the dendrite gets older, and this process is controlled by the rate of diffusion of solute in the liquid.

- Thus the DAS, is largely a function of the solidification time, t_S, and the relationship is of the approximate form:

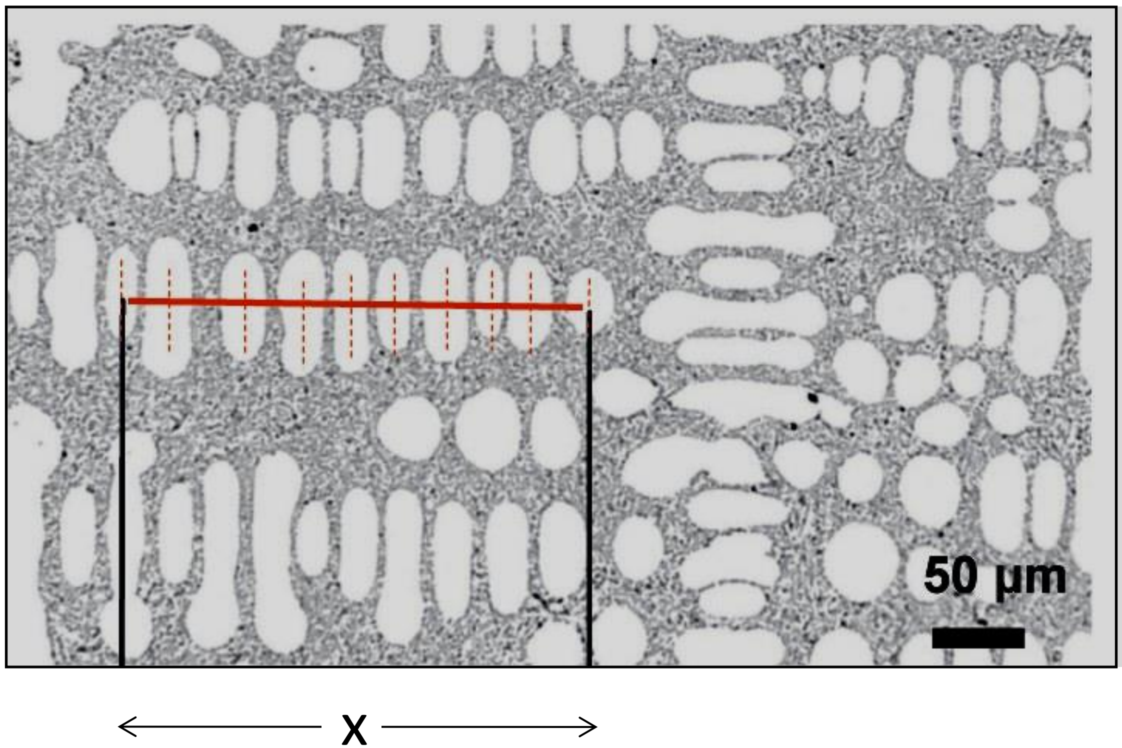
$$\mathbf{DAS \ \infty \ (t_S)^{1/2}}$$

- In practice, DAS is found to be proportional to $(\mathbf{t_S})^{\mathbf{n}}$ where **n = 0.3 – 04**.



Relation between DAS, grain size and local solidification time for Al-4.5Cu alloys

2.1 Measurement of DAS



DAS = $x \div (n - 1)$

n = number of secondary arms
x = distance between n arms

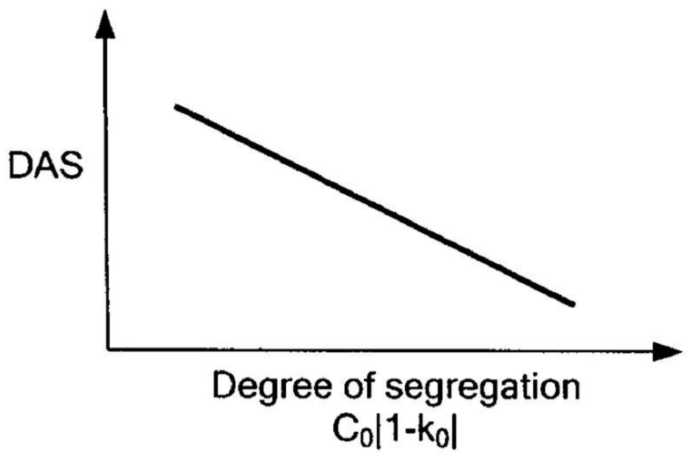
x = 243 µm
n = 10
DAS = 27 µm

- ❑ Take at least 5 secondary arms for one single measurement.
- ❑ Take at least 5 readings for a sample.
- ❑ When x is measured from a photograph, divide the calculated DAS value using the equation with the magnification. For example, if x = 36.5 mm in the above micrograph, and M = x150, then DAS = (36.5/9)/150 = 27 µm

2.2 Factors influencing DAS

1. Solute Concentration

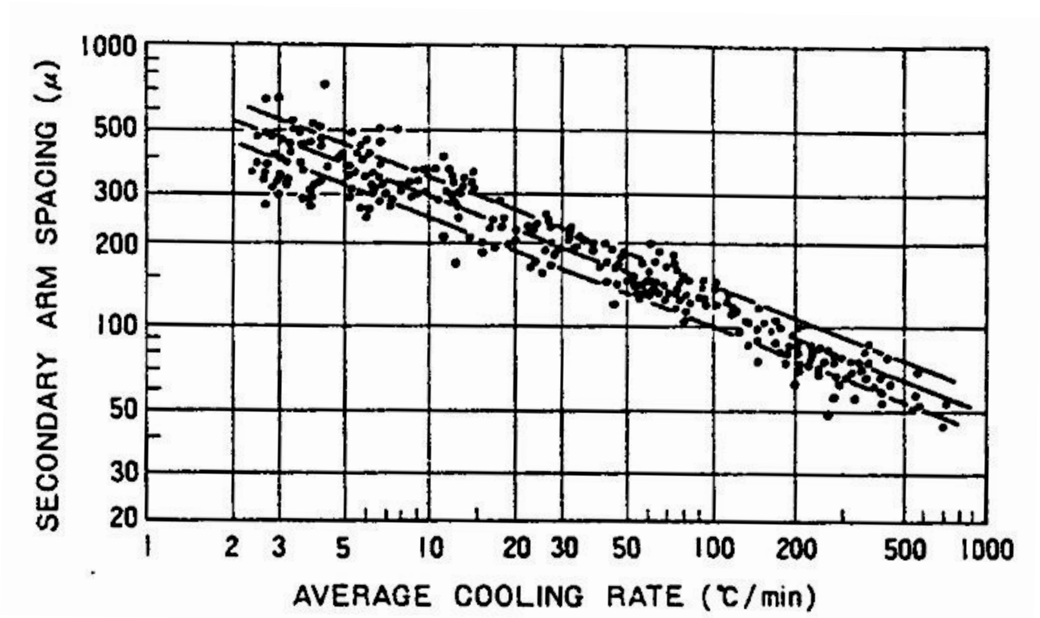
If the freezing condition is constant, a high solute concentration produces more segregation and more instability at the interface yielding crystals with smaller DAS.



variation of DAS with solute segregation

2. Freezing Conditions

If the solute content is constant, a higher freezing rate offers little time for diffusion of segregated solutes, causing more segregation and produces crystals with smaller DAS.



variation of DAS with the cooling rate of some commercial steels containing from 0.1 to 0.9 % C

2.3 DAS and mechanical properties

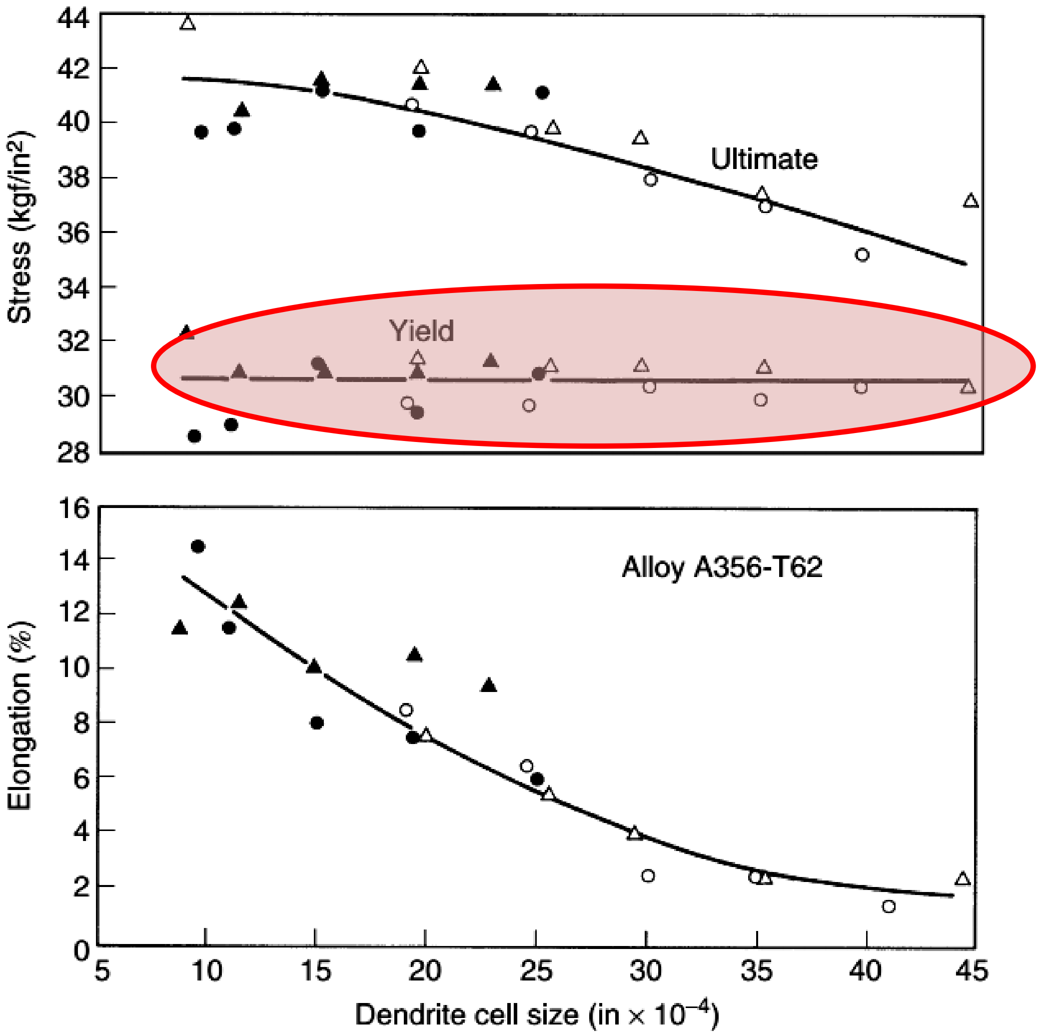


Figure 2.28 Influence of dendrite cell size on tensile properties of a cast alloy (after Spear and Gardner[12]) (courtesy of American Foundrymen's Society)

- The mechanical properties of most cast alloys depend strongly on DAS:
  - **tensile strength, ductility and elongation all increase as DAS decreases**
  - **the freezing condition that enables the production of materials with narrow DAS is the most desirable**

Why does YS relatively insensitive to DAS?

- Effect of a reduced DAS should not be confused with those given by a **grain refinement technique** (by Hall-Petch relation)
  - no grain boundary exists between the arms of a single dendrite
  - dislocation can move freely
  - DAS refinement affects only to the UTS and ductility, not to the yield strength
  - Hall-Petch relation should not apply (which affects only to the yield strength)

Reasons for improvement in properties due to DAS refinement

1. Restricted nucleation of interdendritic phases

- As the DAS becomes smaller, the residual liquid is split up into progressively smaller (often isolated) regions.
  - the presence of foreign nuclei that helps heterogeneous nucleation of interdendritic phases (including gas pores) becomes increasingly less probable
  - thus, unless the concentration of segregated solute reaches a value at which homogeneous nucleation can occur, the new phase will not appear
  - thus as DAS decreases, there becomes a cut-off point at which gas pores cannot appear. Effectively, there is simply insufficient room for the bubble!

- In summary, therefore, we can see that as DAS is reduced, the interdendritic structure becomes, on average, cleaner and sounder. These qualities are probably significant contributors to improved properties.

2. Restricted growth of interdendritic phases

- A decrease in DAS causes a reduction in size of the interdendritic phases

  for example, Si particles and Fe-rich intermetallics in Al-Si alloys, which tend to reduce the mechanical properties of Al-Si alloy

- Both the size of secondary phases and DAS are dependent on the same key factor, the time available for growth

  thus local solidification time controls the size of both dendrite arms and interdendritic phases

3. Improved response to homogenization treatment

Index of residual microsegregation, $$\delta = \frac{C_M - C_m}{C^o_M - C^o_m}$$

C_M = maximum solute concentration of element (in interdendritic spaces) at time t
C_m = minimum solute concentration of element (in centre of dendrite arms) at time t
C^o_M =maximum initial concentration of element
C^o_m = minimum initial concentration of element.

Before homogenization treatment, $\delta = 1$

After homogenization treatment, $\delta = 0$ ➔ Perfect homogenization

After any real homogenization, $\delta = \exp(-\pi^2 Dt / l_o^2)$

As DAS is decreased, δ is reduced and the degree of homogenization is improved

D = diffusion coefficient
l_0 = DAS/2

To summarize the effect of DAS on heat-treatment response:

- As DAS is reduced, the speed of homogenization is increased, allowing more complete homogenization, giving more solute in solution and so greater strength from the subsequent precipitation reaction.

- Speed of solution is also increased, allowing a greater proportion of the non-equilibrium second phase to be dissolved. The smaller numbers and sizes of remaining particles, if any, and the extra solute usefully in solution, will bring additional benefit to strength and toughness.

Next Class

MME **345**, Lecture **B:06**

Solidification and Crystallisation

5. Formation and control of granular crystals