

انجماد فلزات

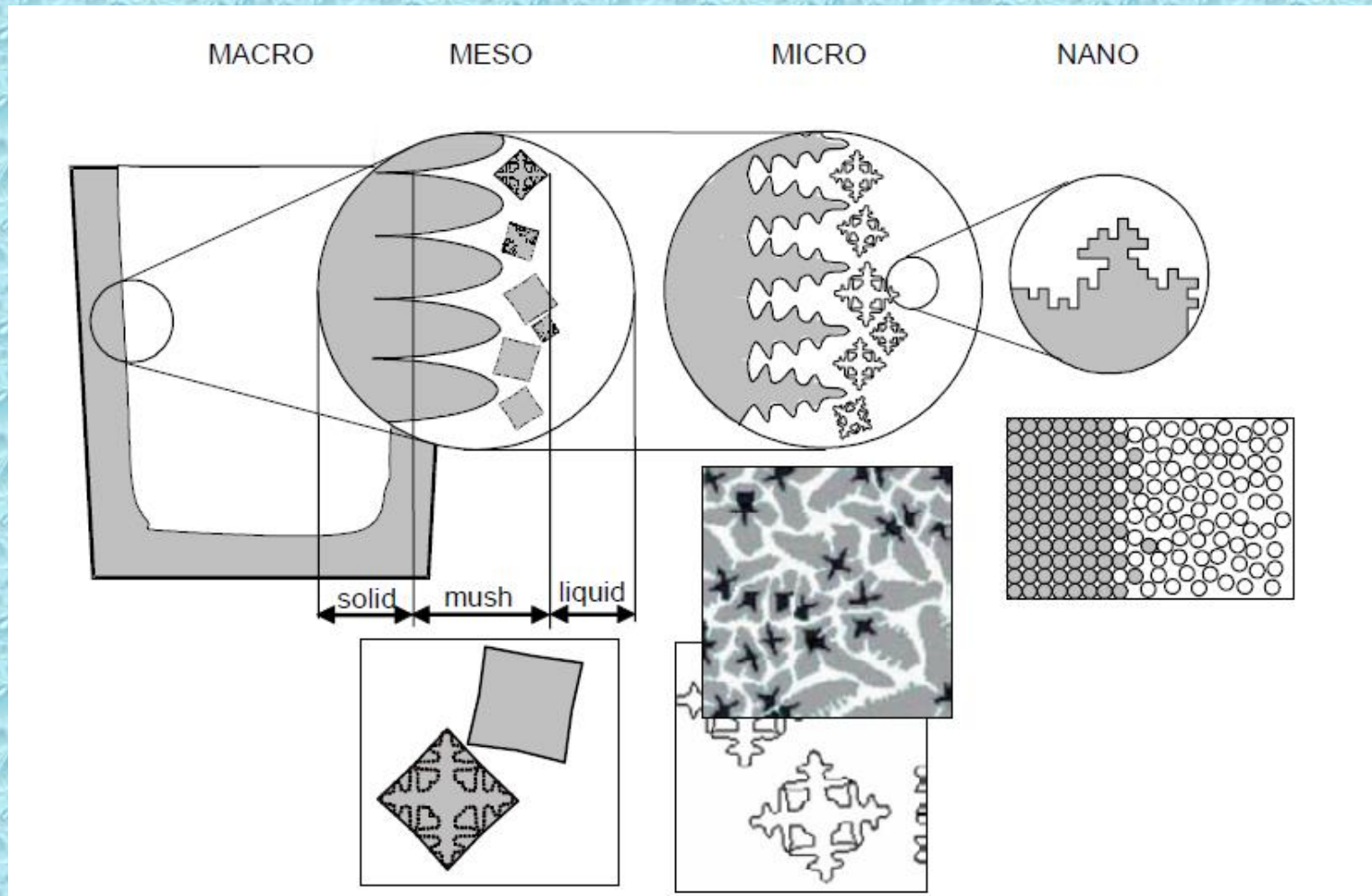
دکتر وحید ابویی مهریزی

مقطع کارشناسی

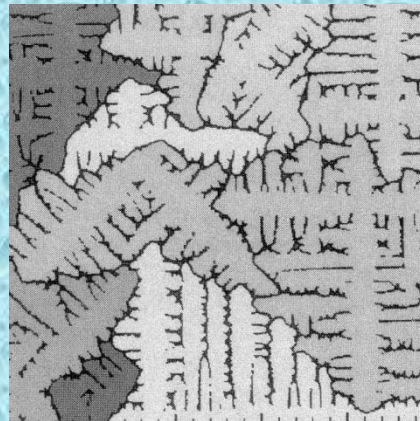
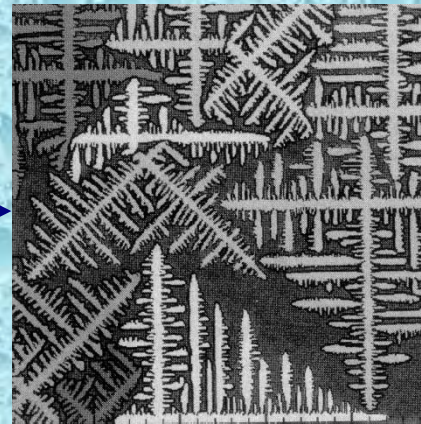
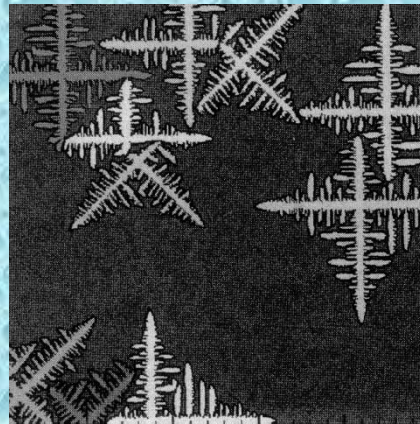
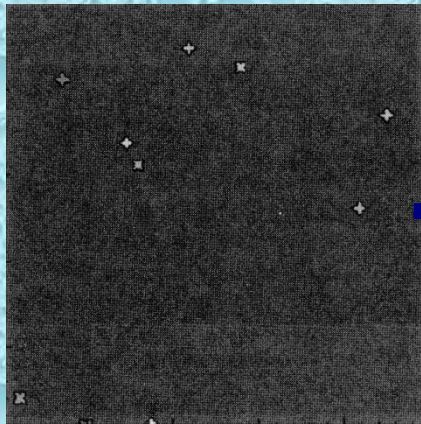


انجماد و ساختار فلزات

انجماد در ابعاد مختلف



مراحل مختلف انجماد

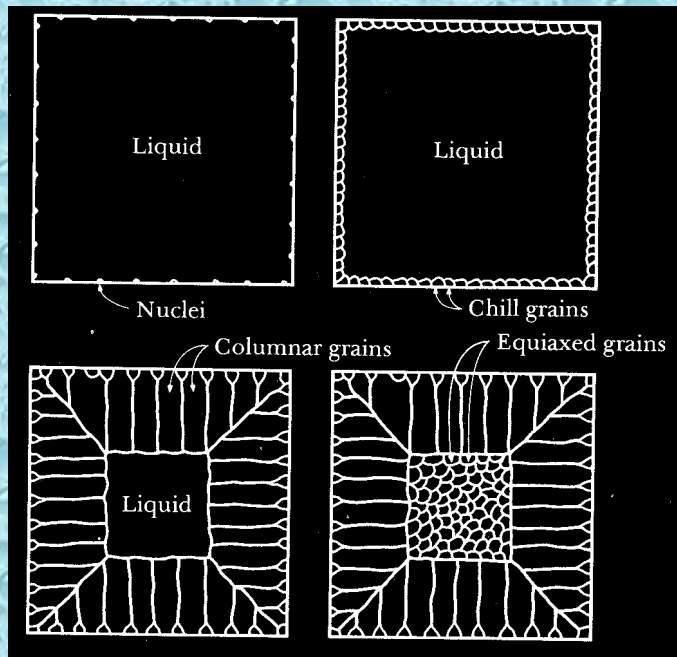


Microstructure

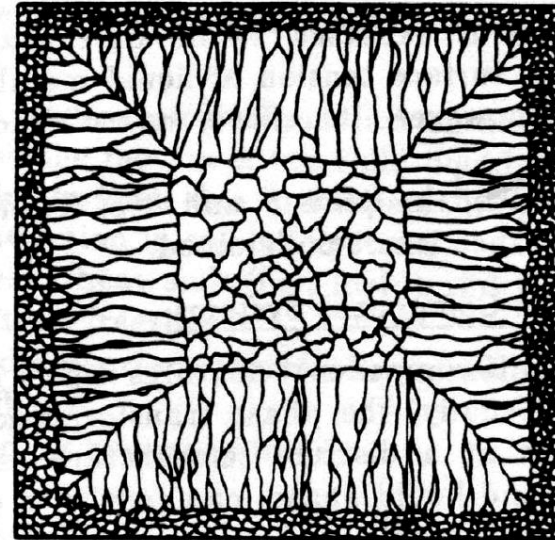
Equi-axed

Columnar

Casting or Ingot
Structure

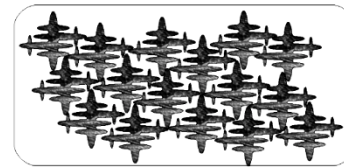
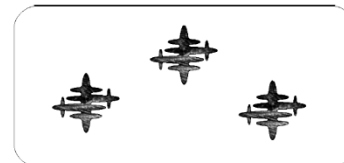


ANISOTROPY

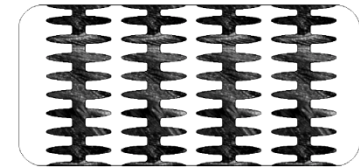
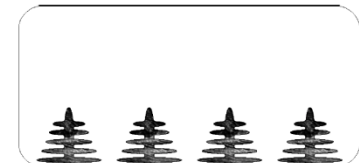


PHYSICAL PHENOMENA (5)

INTERPHASE BOUNDARY MORPHOLOGY



EQUIAXED



COLUMNAR

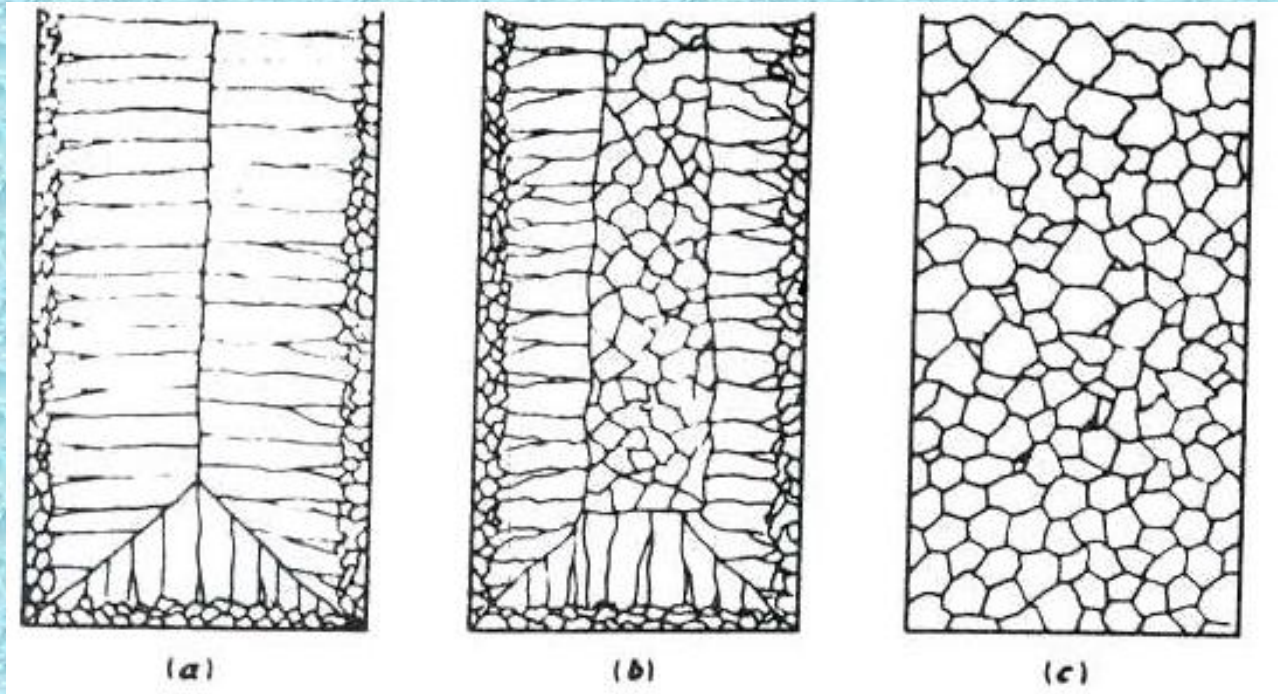
Important parameters

Microstructure

Equi-axed

Columnar

- **Super Heat**
- **Cooling Rate**
- **Temperature Gradient**
- **Chemical composition**
- **Grain Refiners**



Casting structures

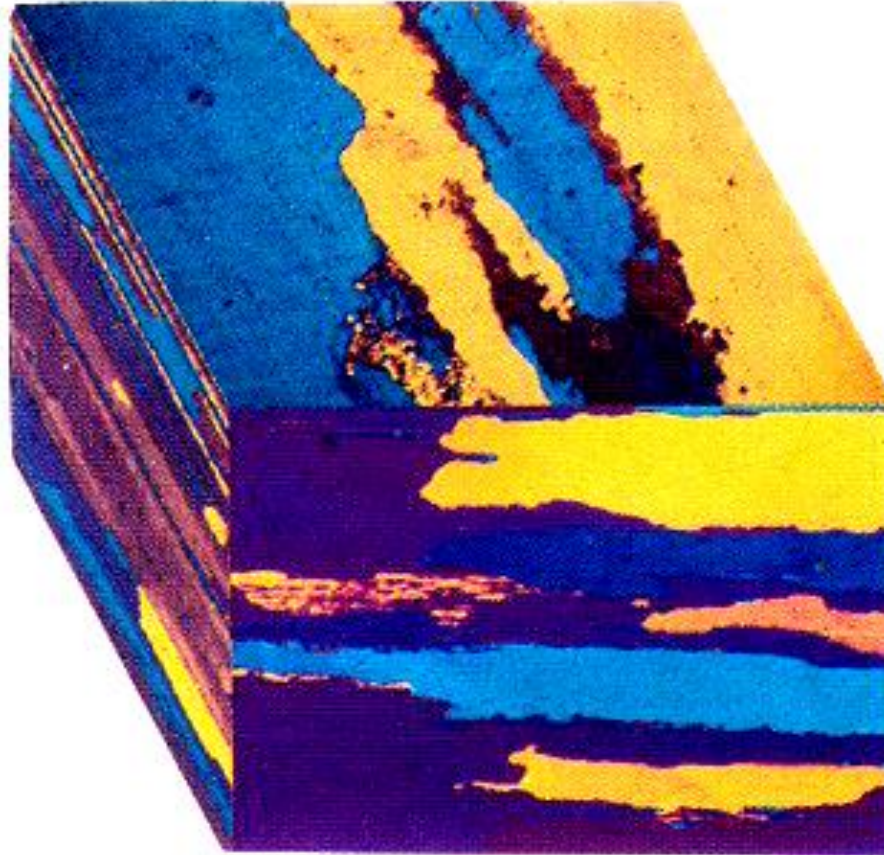
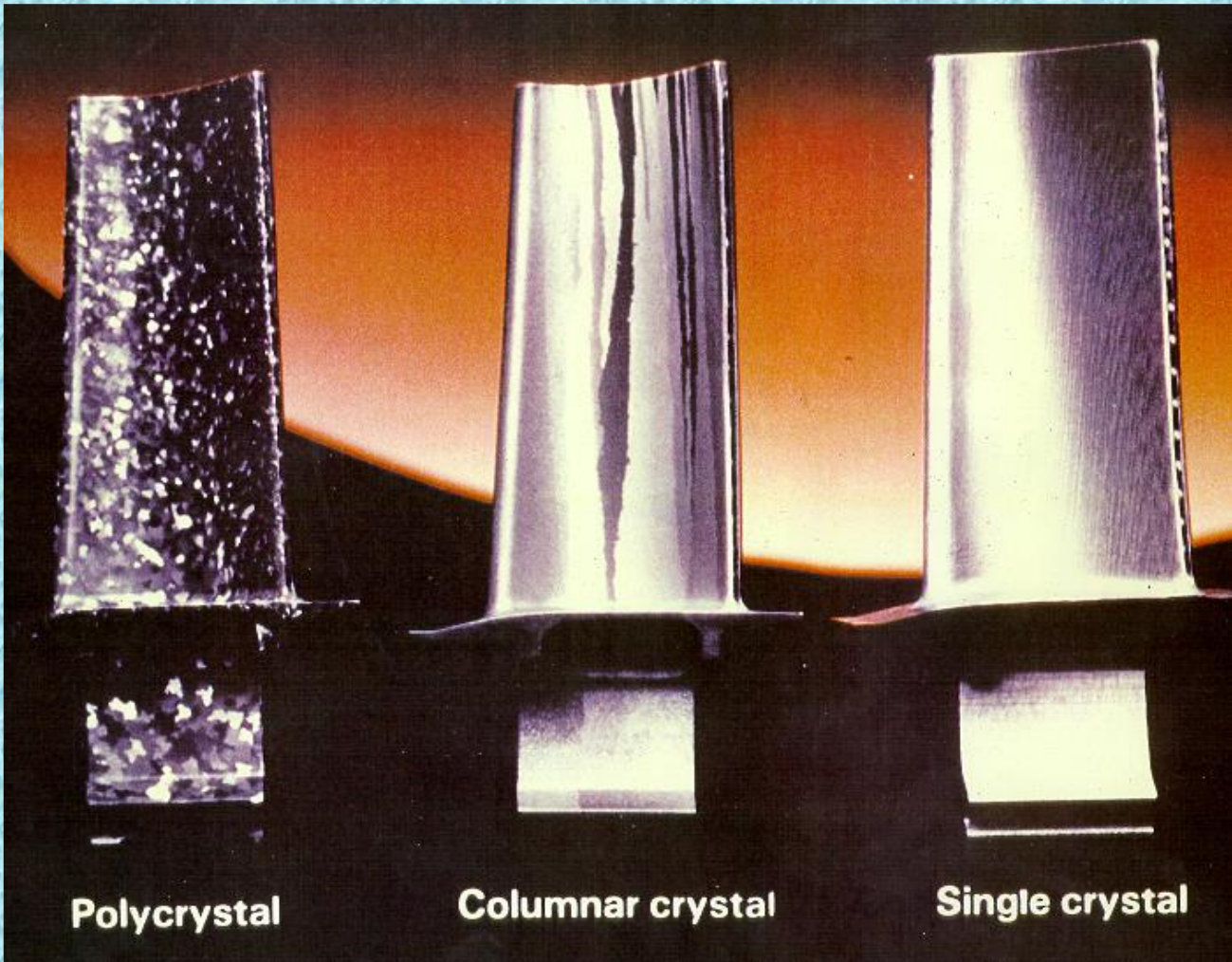


FIG. 8.2 Three-dimensional grain structure in a rolled Al-Li plate

Controlled grain structure in turbine blades:



Polycrystal

Columnar crystal

Single crystal

Equi-axed

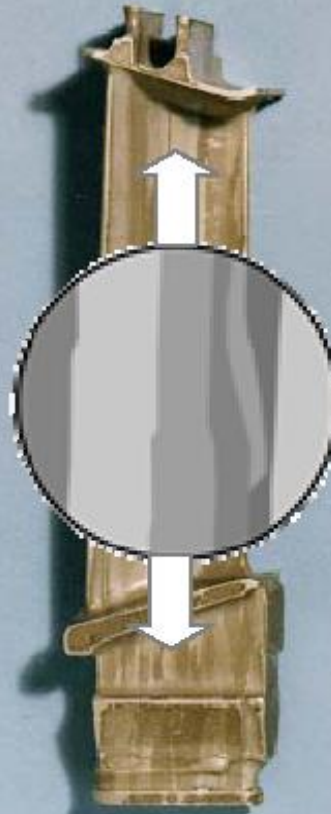
Directionally solidified (DS)

Single Crystal (SC)

Improvements in blade microstructure



**Equiaxed
Crystal Structure**



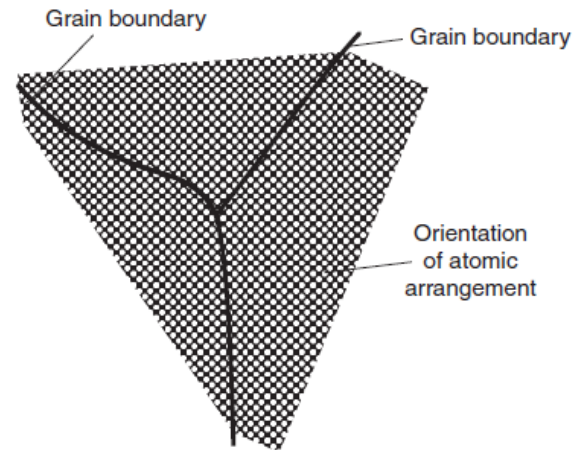
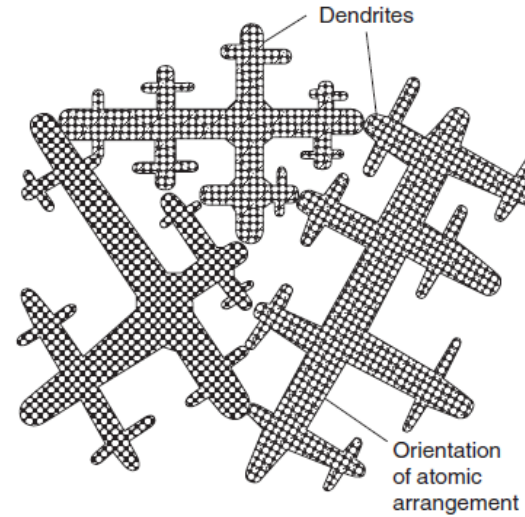
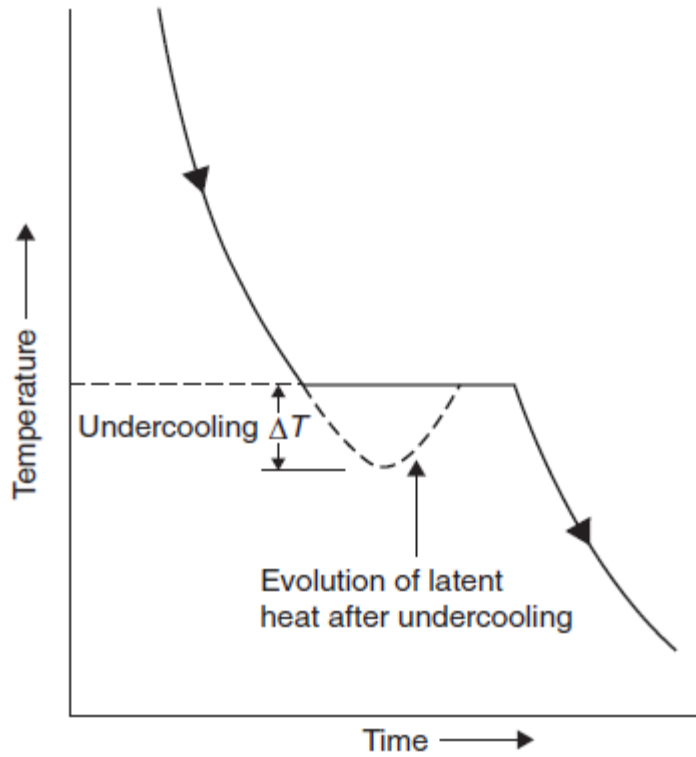
**Directionally
Solidified Structure**



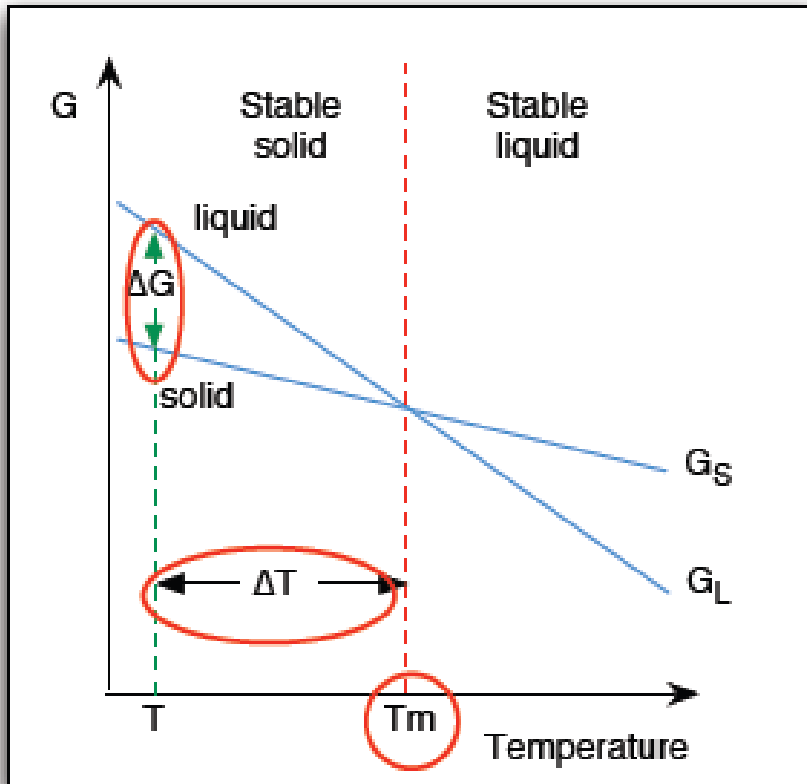
Single Crystal

جوانه زنی

فرایند انجماد = جوانه زنی + رشد

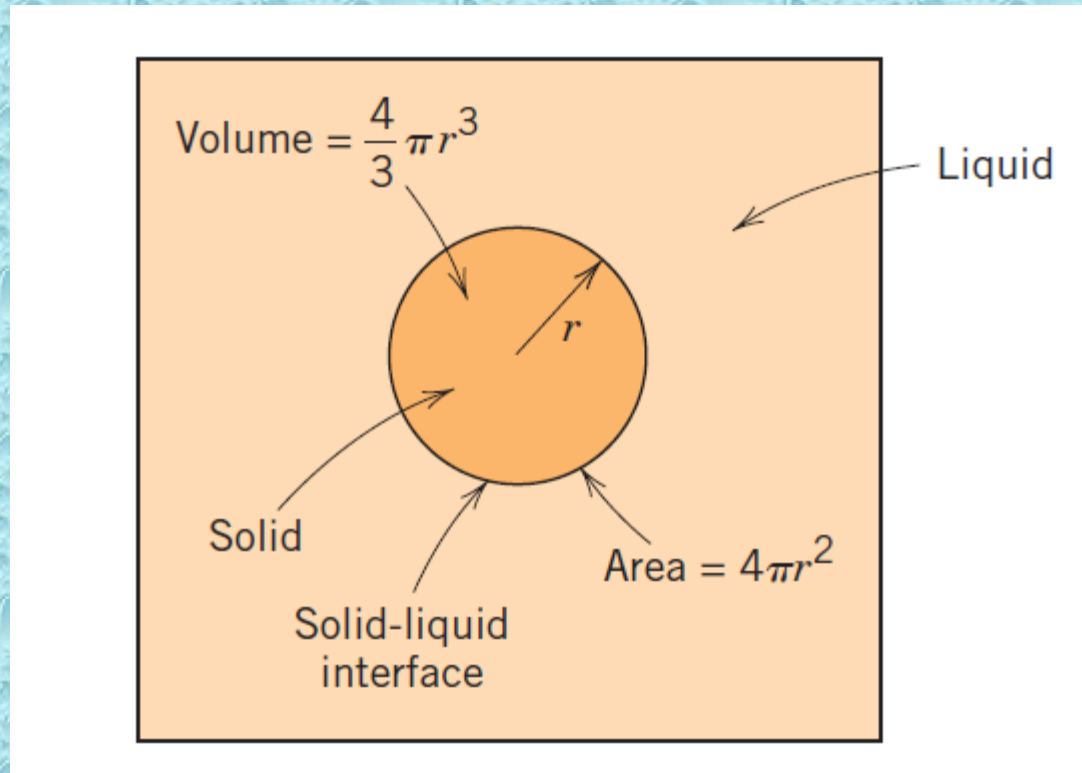
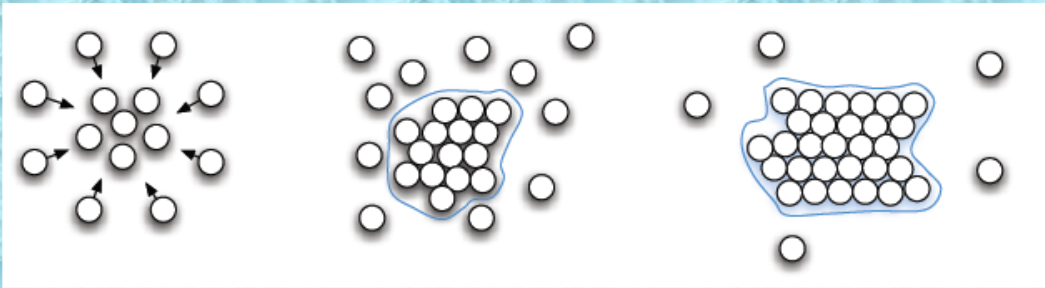


نیروی محرکه جوانه زنی



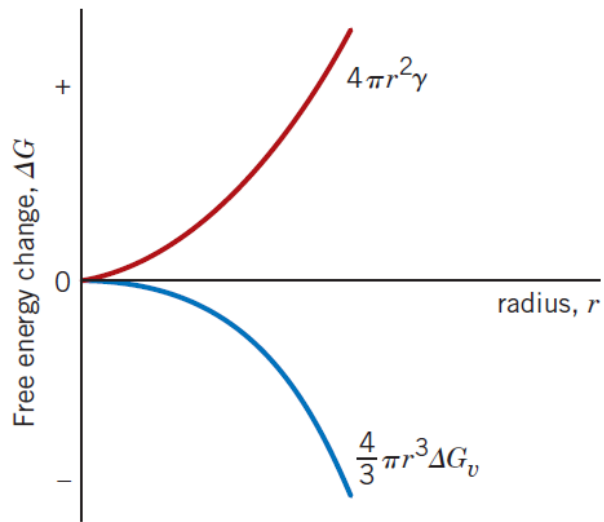
$$\Delta G_V$$

$$= \frac{L_V \Delta T}{T_m}$$

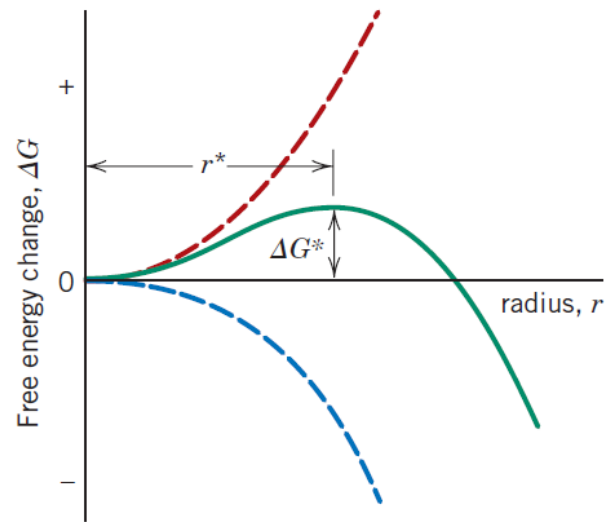


جوانه زنی همگن

$$\Delta G = \frac{4}{3} \pi r^3 \Delta G_v + 4\pi r^2 \gamma$$



(a)



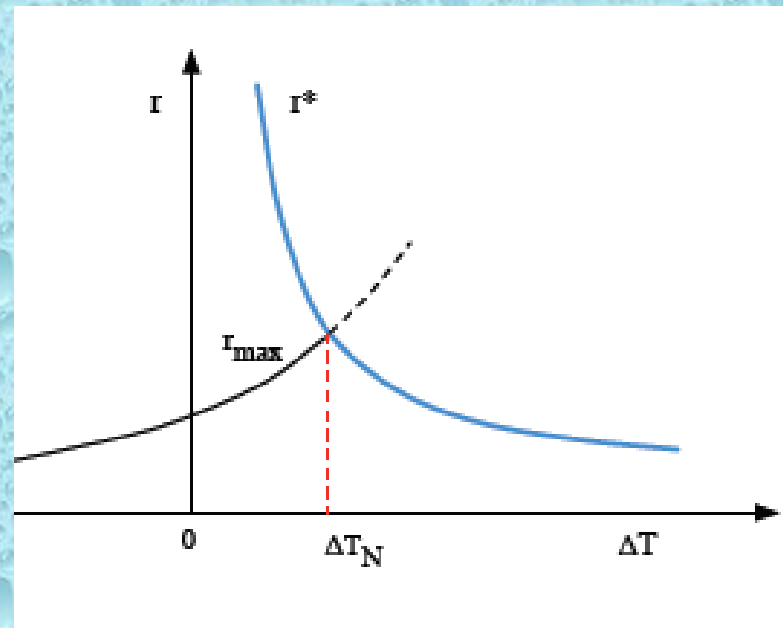
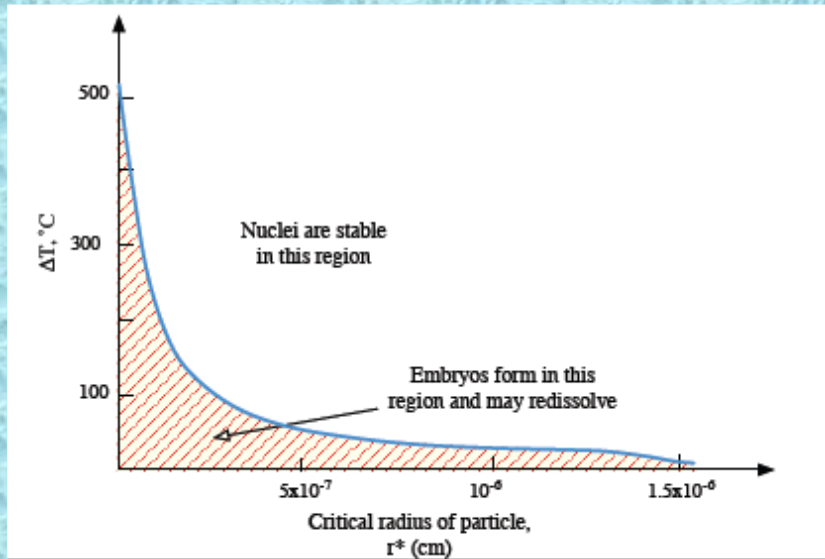
(b)

$$\frac{d(\Delta G)}{dr} = \frac{4}{3}\pi \Delta G_v (3r^2) + 4\pi \gamma (2r) = 0$$

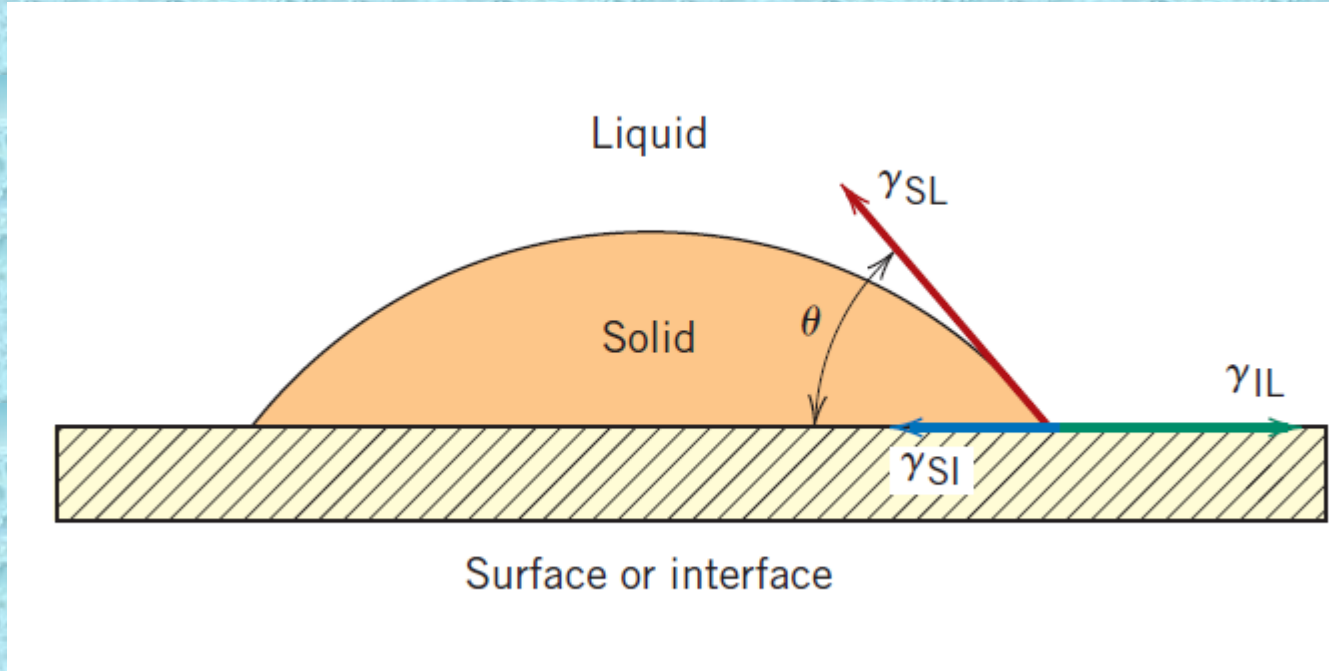
$$r^* = -\frac{2\gamma}{\Delta G_v}$$

$$\Delta G^* = \frac{16\pi\gamma^3}{3(\Delta G_v)^2}$$

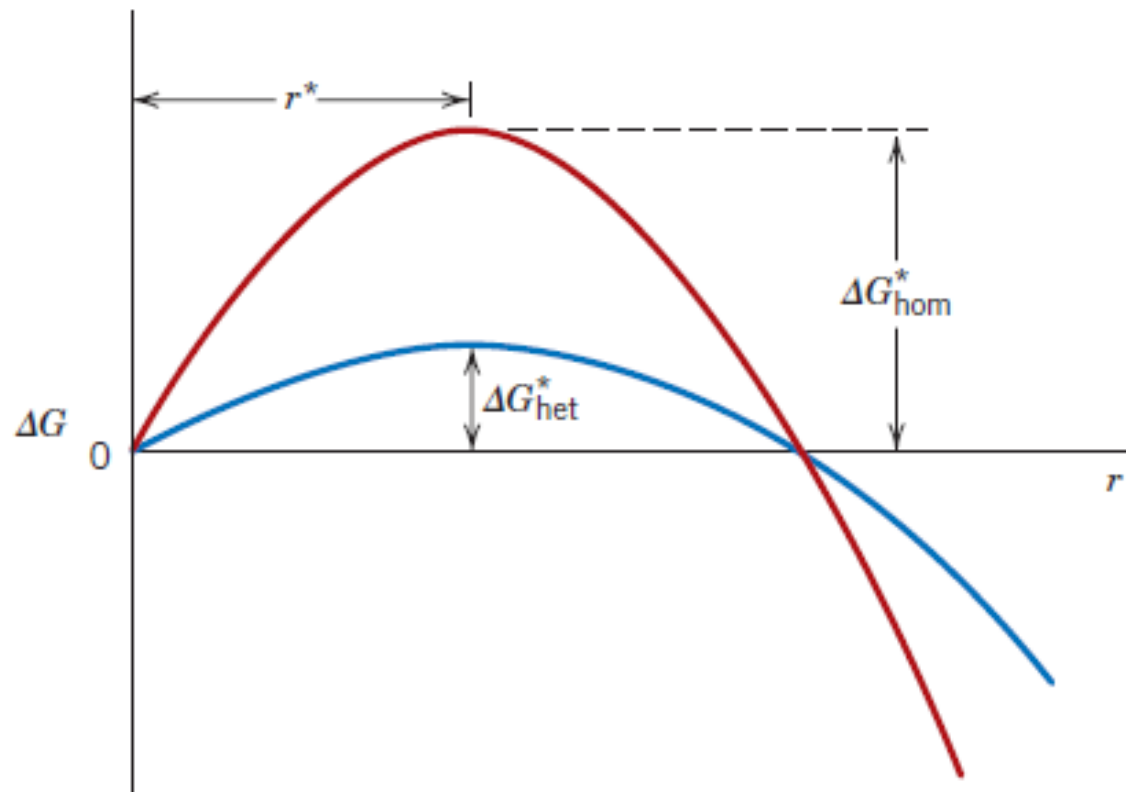
تأثير مادون انجماد بر شعاع بحرانی



جوانه زنی نا همگن



$$\gamma_{IL} = \gamma_{SI} + \gamma_{SL} \cos \theta$$



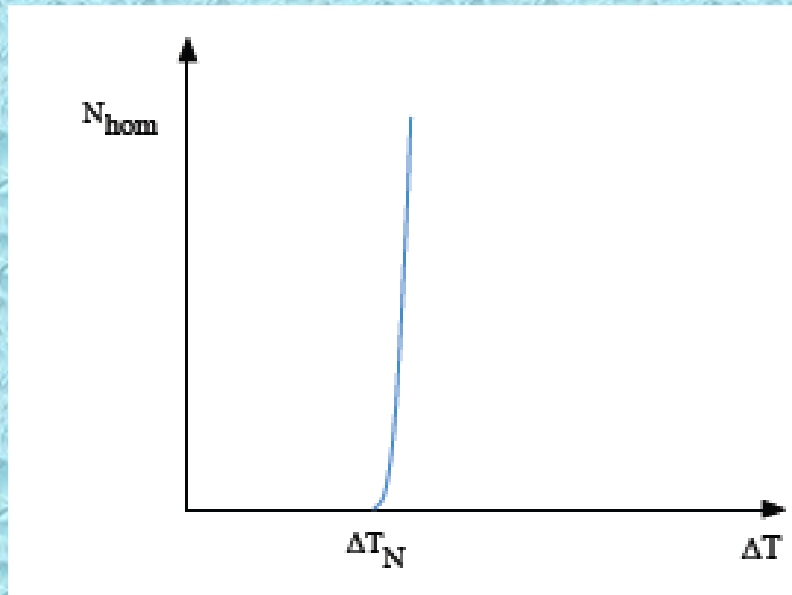
$$r^* = -\frac{2\gamma_{SL}}{\Delta G_v}$$

$$\Delta G^* = \left(\frac{16\pi\gamma_{SL}^3}{3\Delta G_v^2} \right) S(\theta)$$

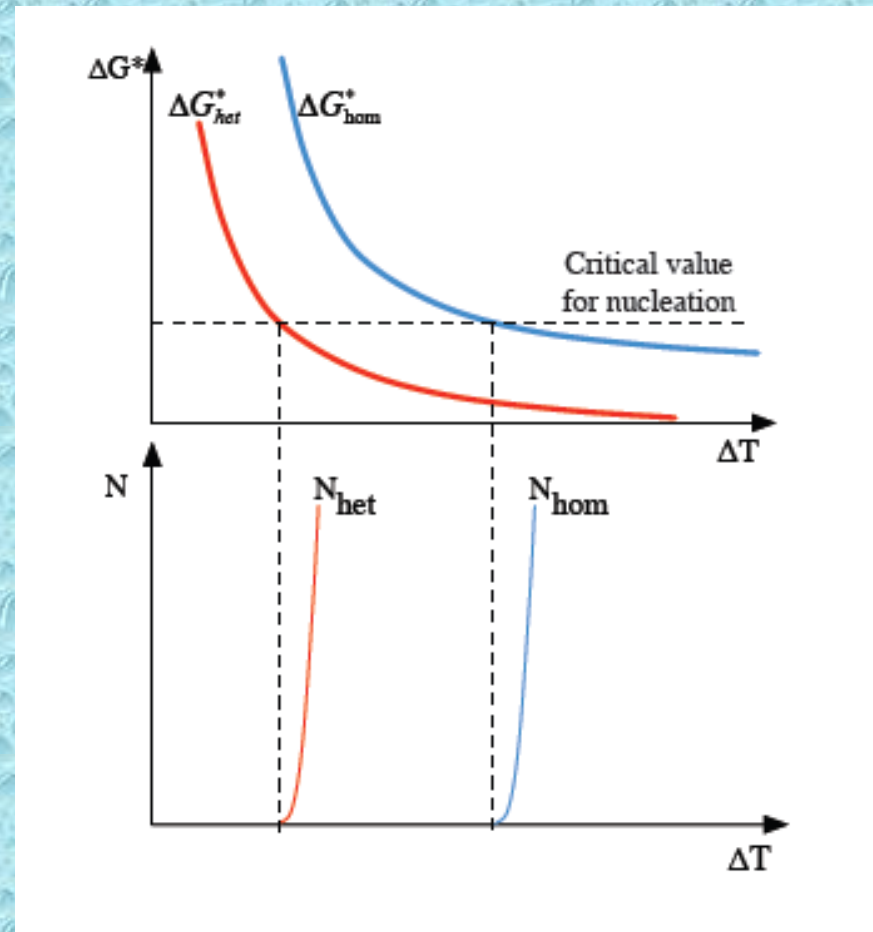
$$\Delta G_{het}^* = \Delta G_{hom}^* S(\theta)$$

$$S(\theta) = \frac{(2 + \cos\theta)(1 - \cos\theta)^2}{4} < 1$$

سرعت جوانه زنی



$$N_{\text{hom}} = f_o C_o e^{-\frac{\Delta G_{\text{hom}}^*}{kT}} \text{ nuclei/m}^3$$



رشد

در بعد میکروسکوپی

مکانیزم های رشد

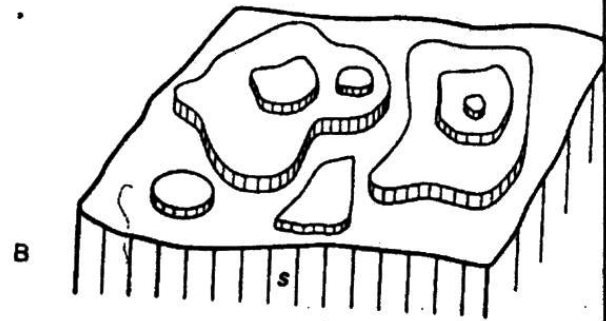
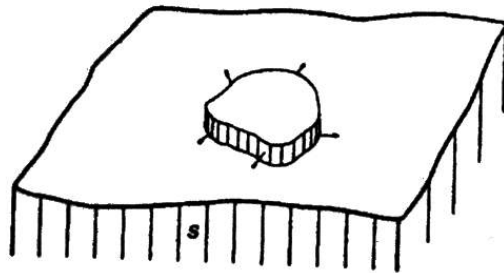
Continuous

$$V=B \Delta T_i$$

Disk shape

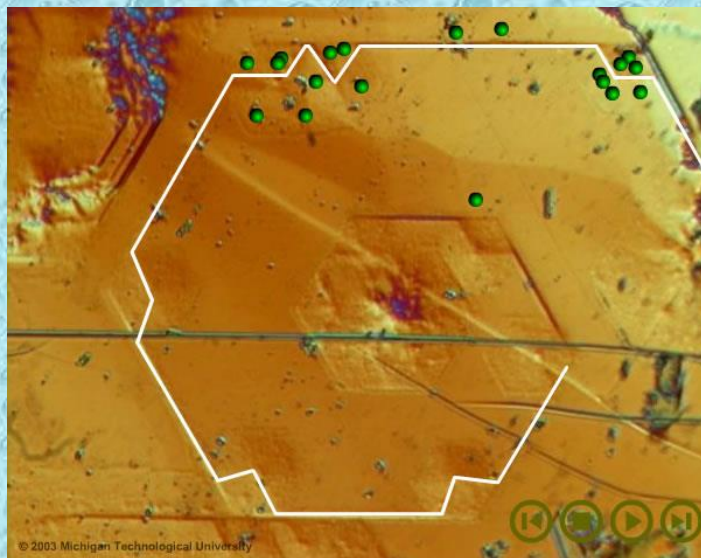
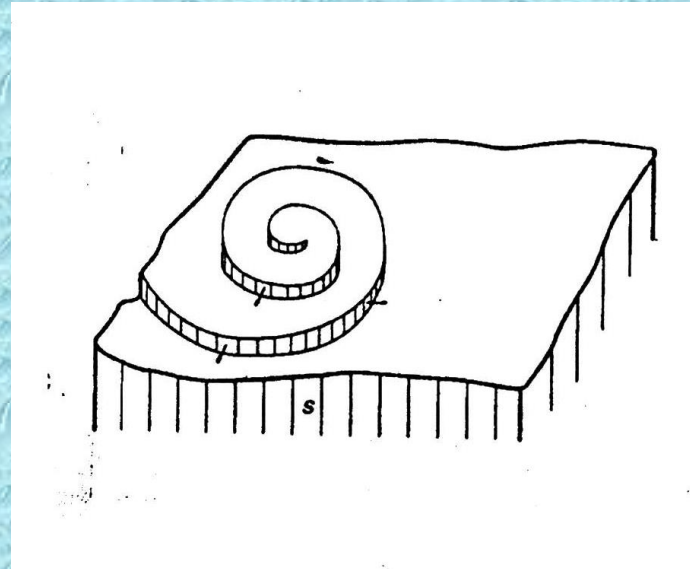
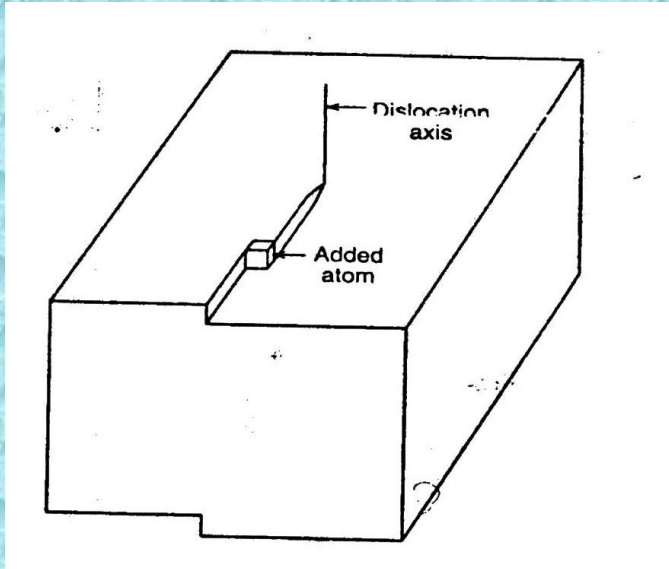
$$V=A \exp (B/\Delta T_i)$$

Disk

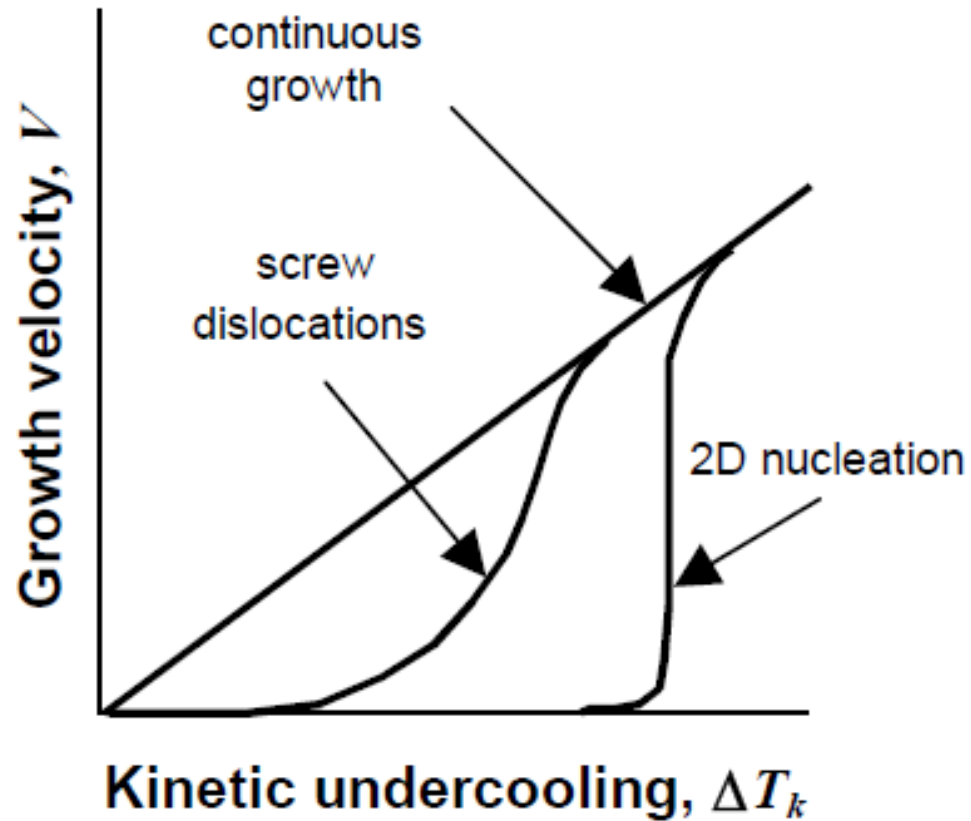


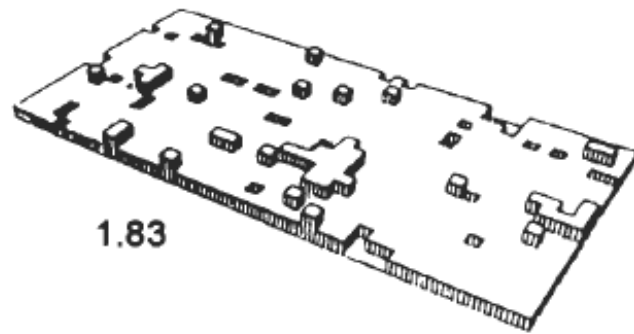
Spiral Growth

$$(B = V \Delta)^2 \tau_i$$

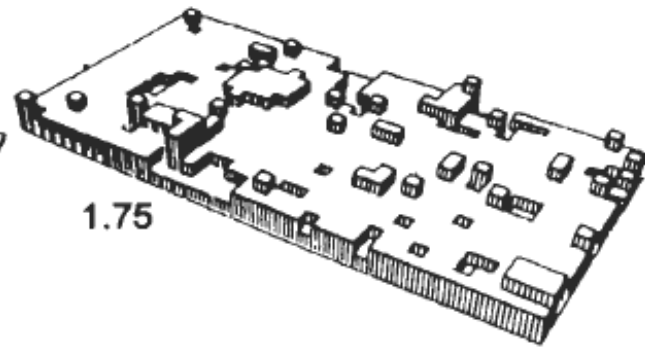


مقایسه سرعت در انواع مختلف رشد

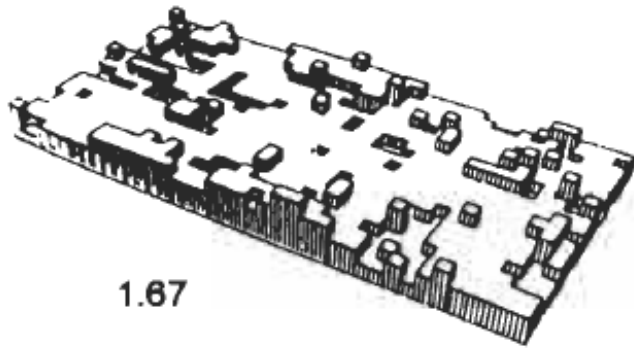




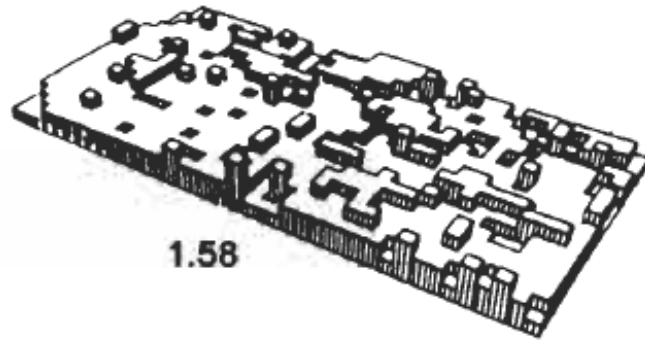
1.83



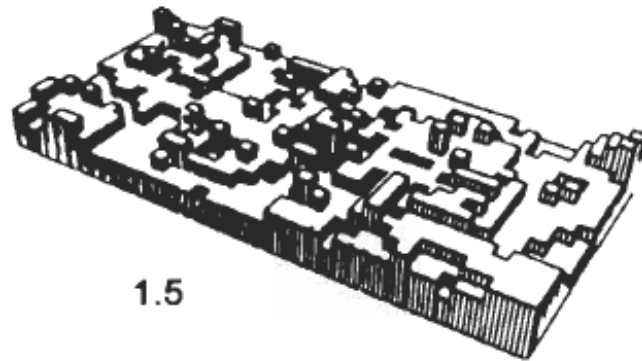
1.75



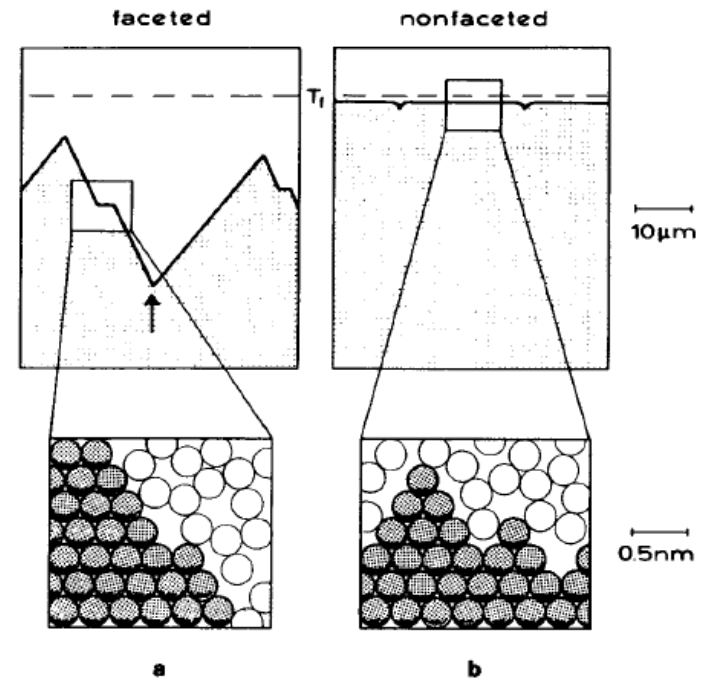
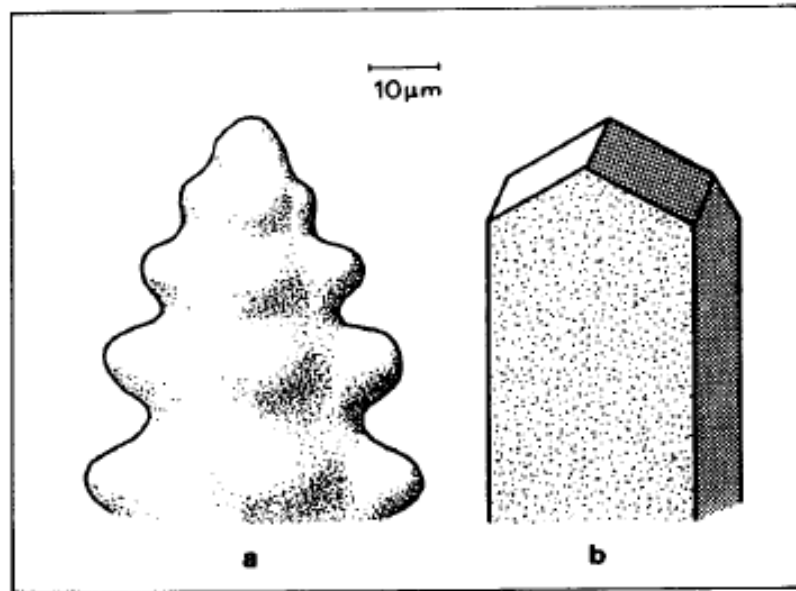
1.67

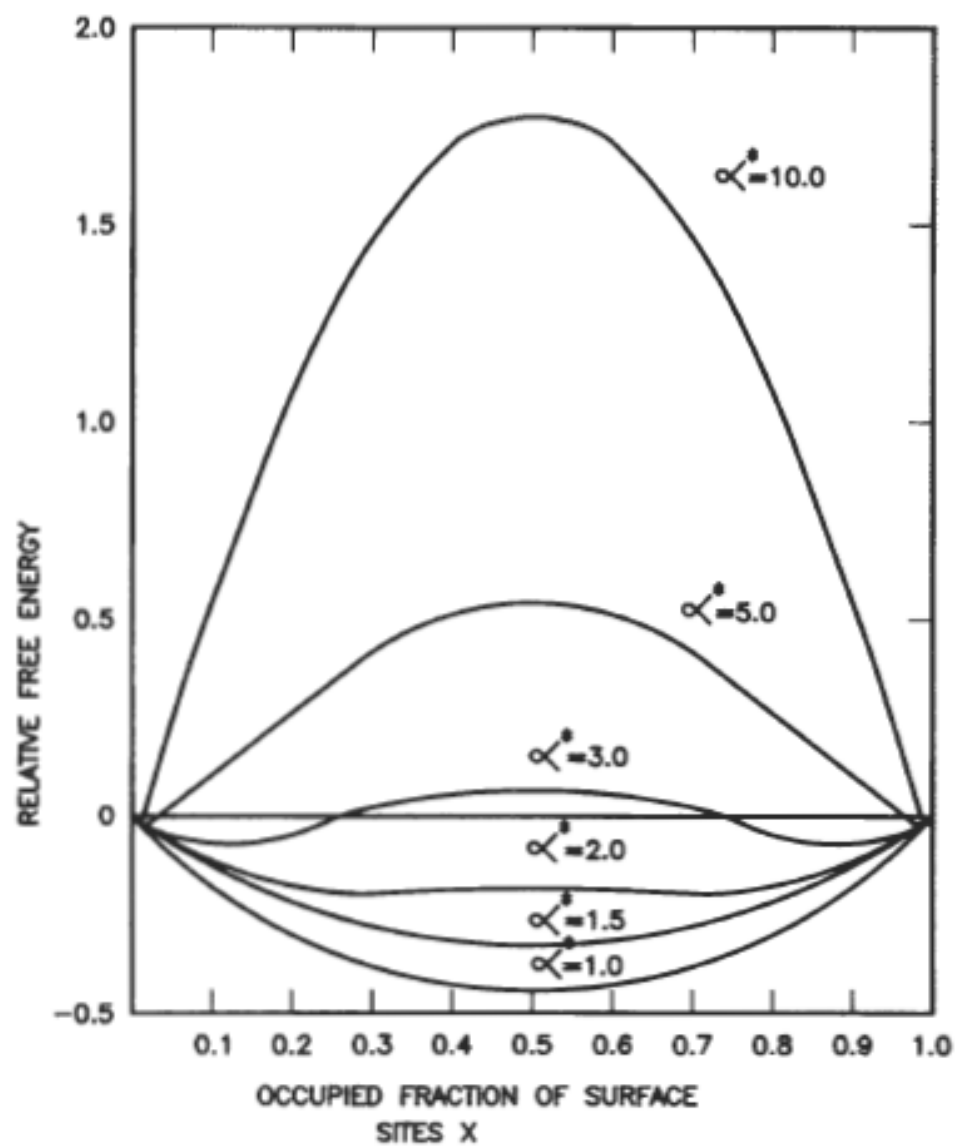


1.58



1.5



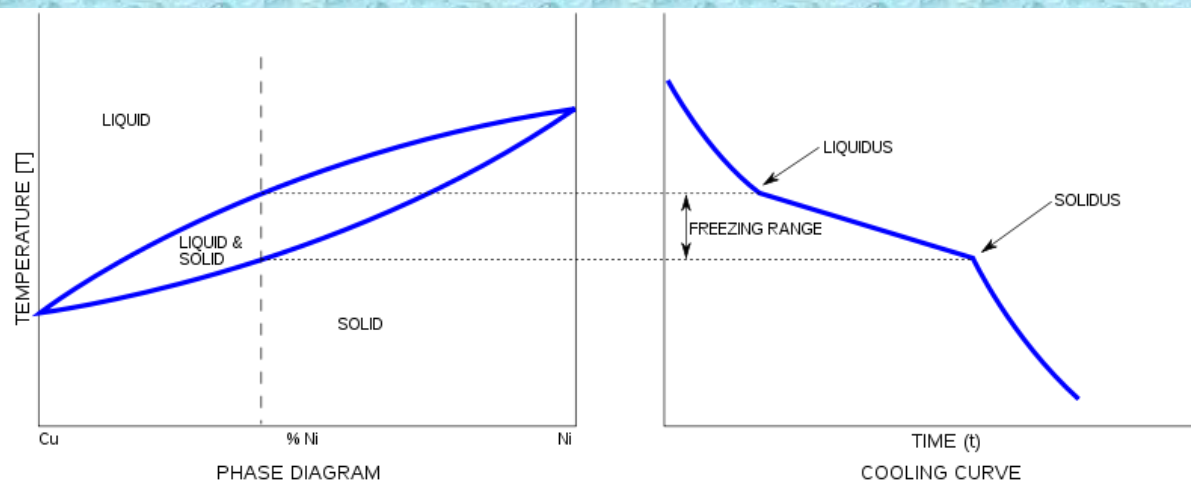
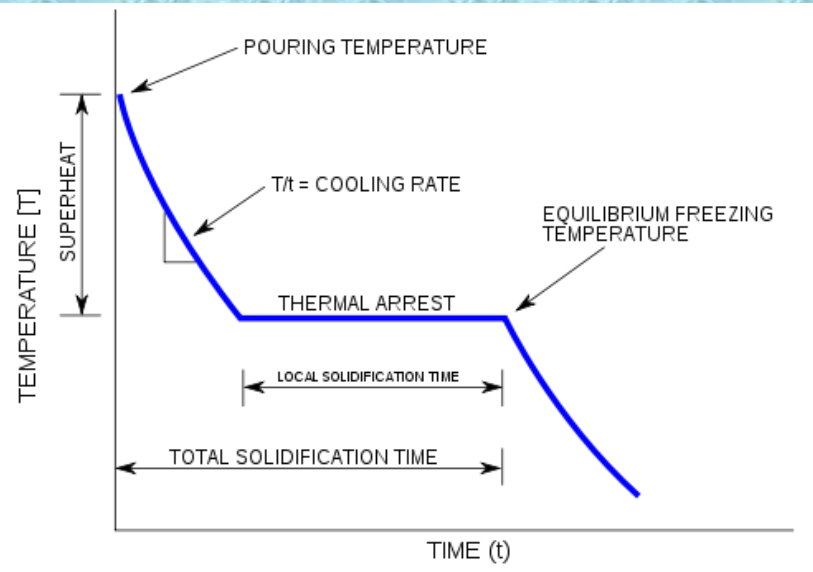


انجماد

در فلزات خالص و آلیاژها

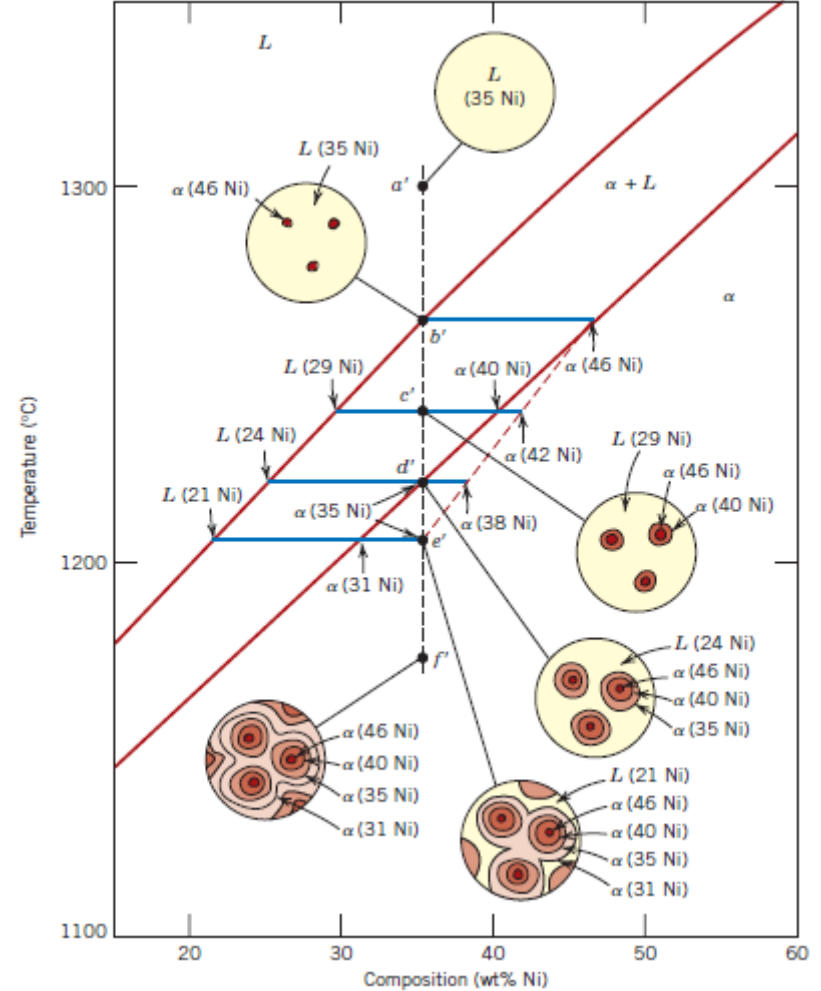
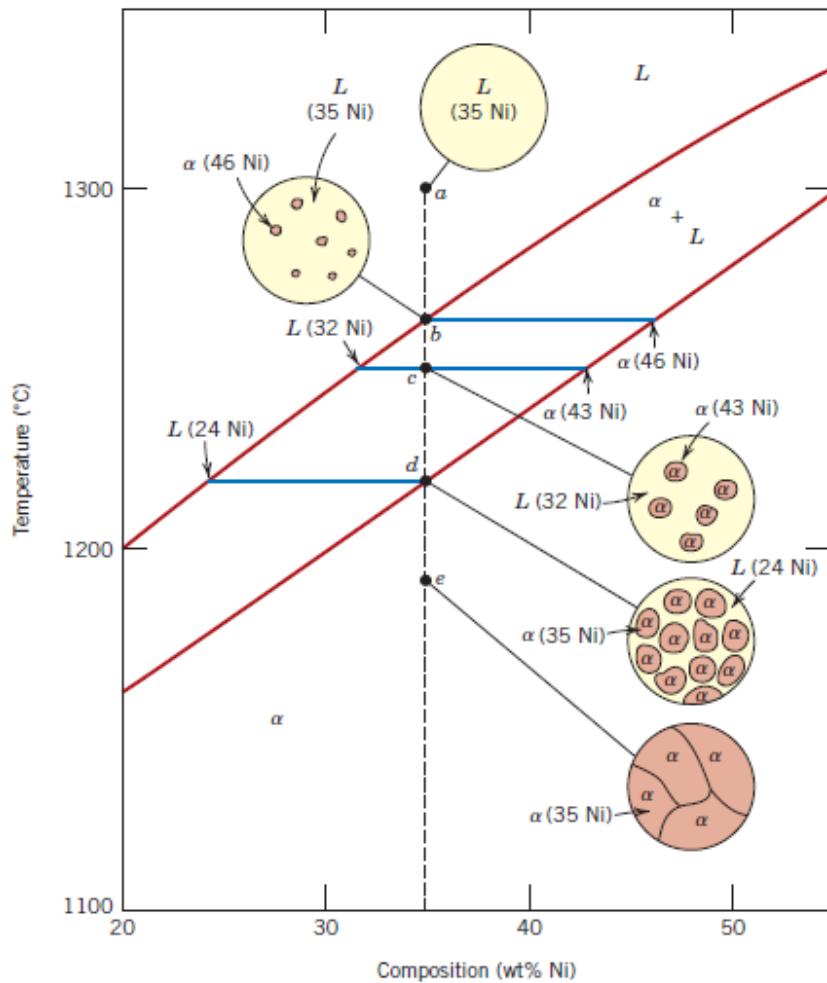
انجماد در فلزات خالص و آلیاژها

فلز خالص



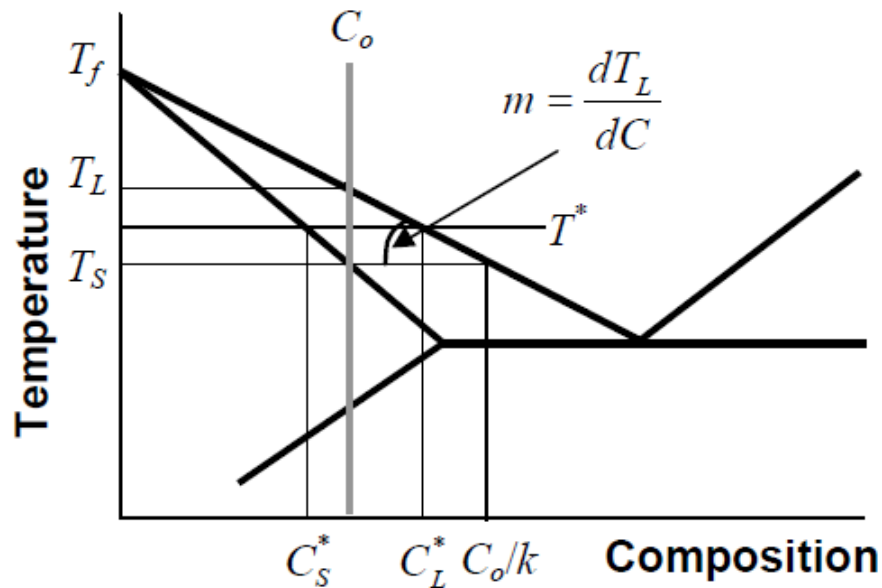
آلیاژ

انجماد تعادلی و غیر تعادلی



چند پارامتر :

$$k = (C_S^*/C_L^*)_{T,P}$$



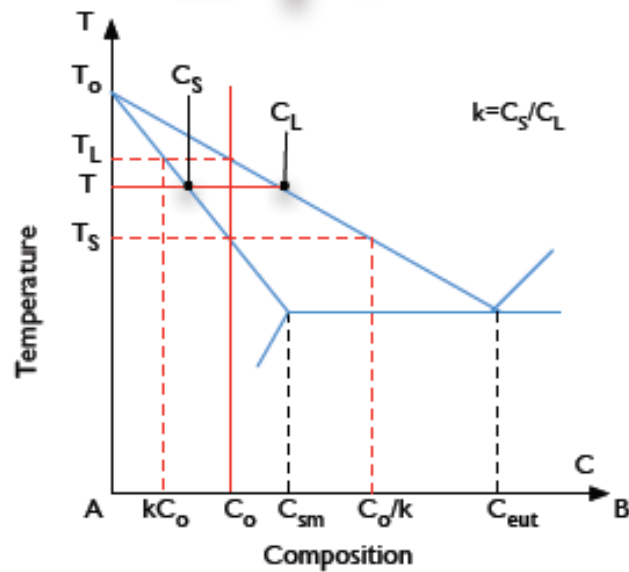
سرعت رشد: R

شیب دمایی: $G = dT/dx$

قابلیت نفوذ: D

ضریب توزیع تعادلی: $K = C_s / C_l$

Equilibrium Solidification

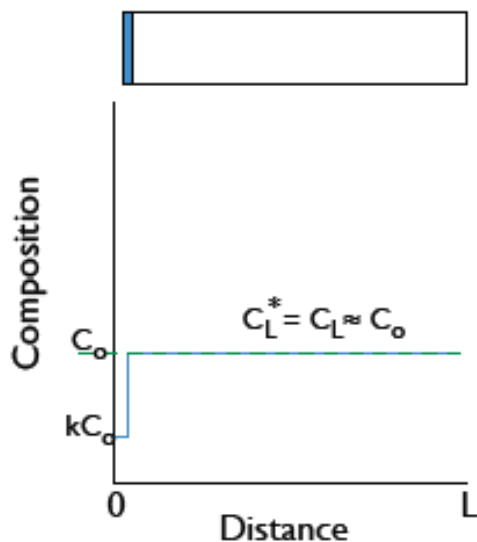


Complete Diffusion in Solid and Liquid Respectively

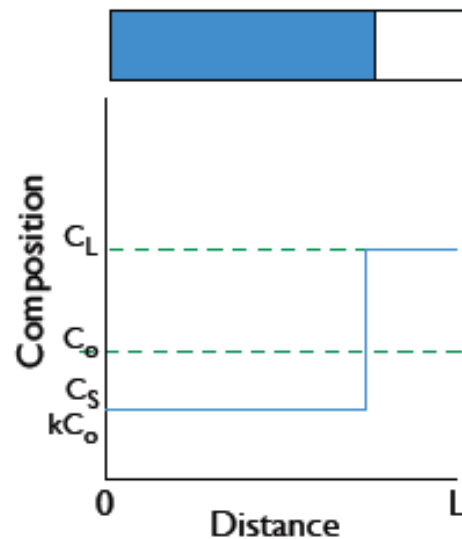
$$\chi_s C_s + \chi_l C_l = C_o$$

Lever Rule

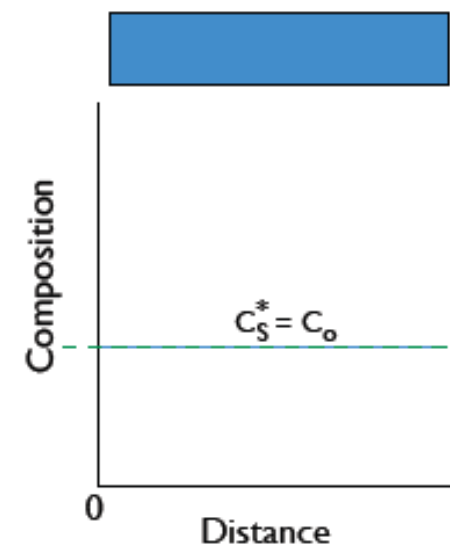
Start of Solidification



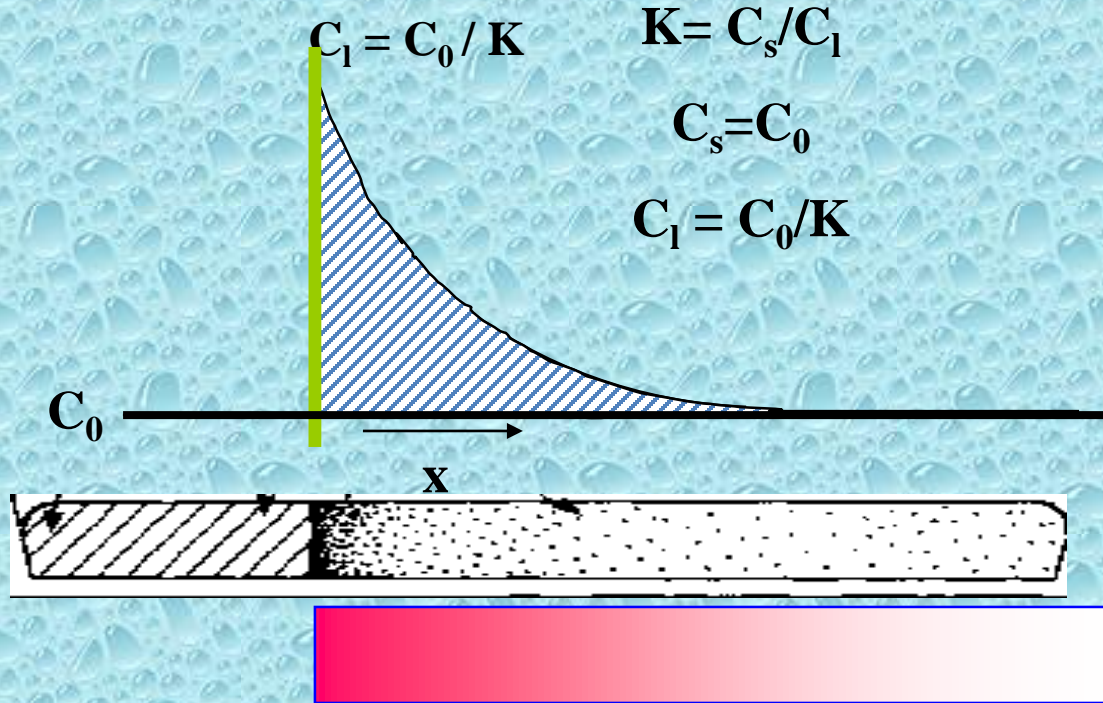
At Temperature T



End of Solidification



تغییرات غلظت در جلوی
جبهه انجماد در انجماد
غیر تعادلی

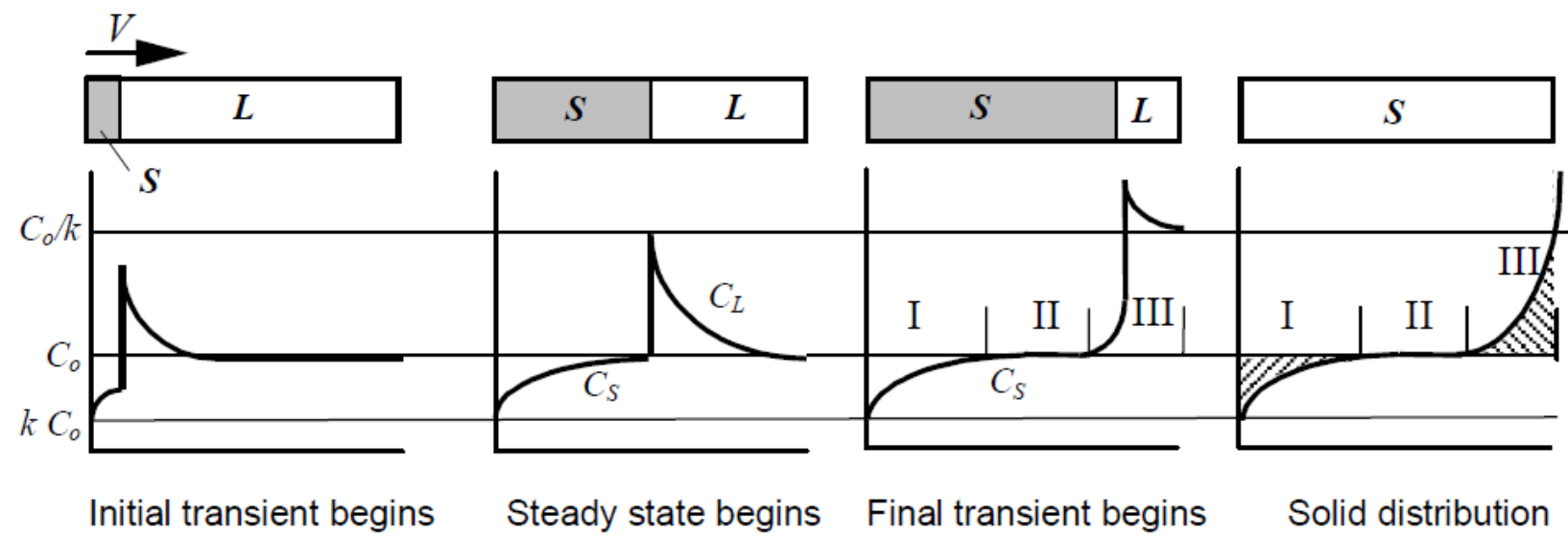
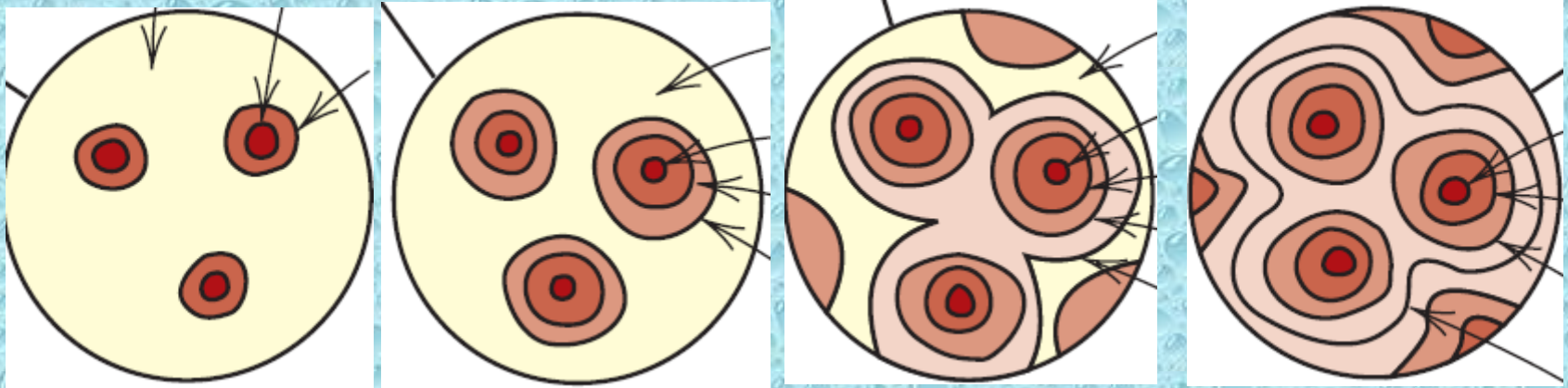


$$C = C_s \left[1 + \frac{1 - K_s}{K_s} \exp \left(- \frac{Rx}{D} \right) \right]$$

$$T_l = T_m - mc_s \left[1 + \frac{1 - K_s}{K_s} \exp \left(- \frac{Rx}{D} \right) \right]$$

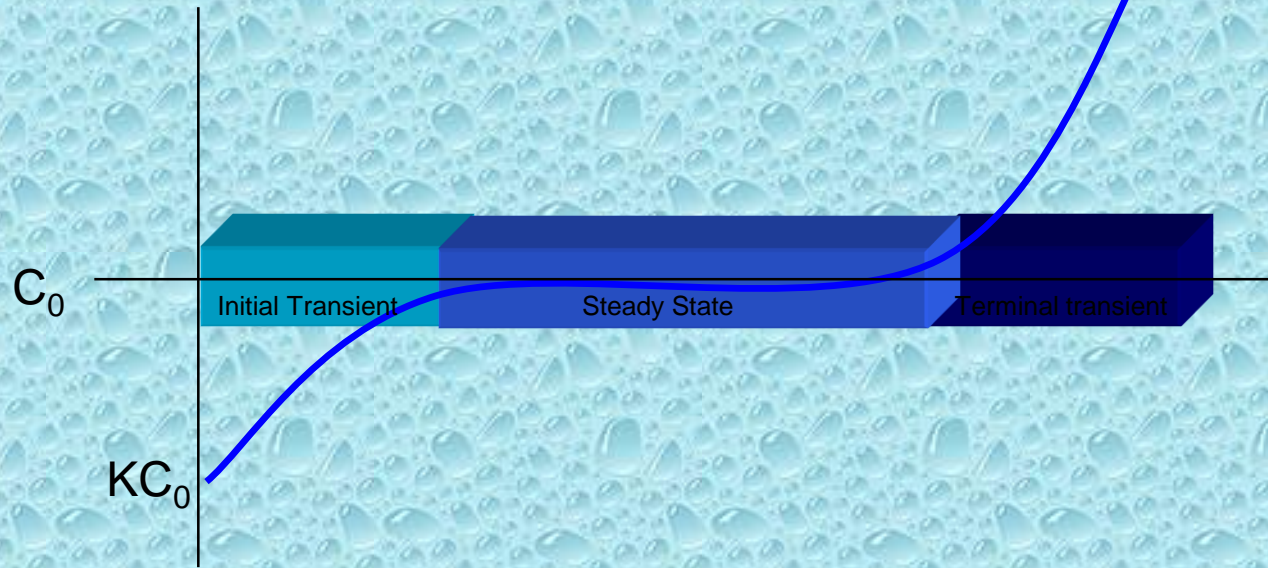
دمای تعادلی مذاب نقاط مختلف جلوی فصل مشترک

انجماد غیر تعادلی و تغییر ترکیب در جامد

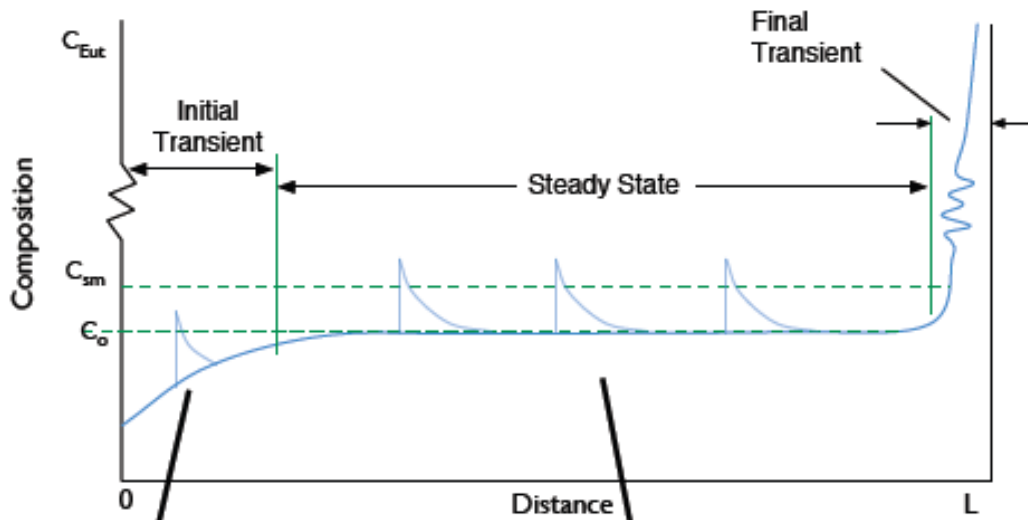


انجماد غیر تعادلی و منطقه پایدار

$$K < 1$$

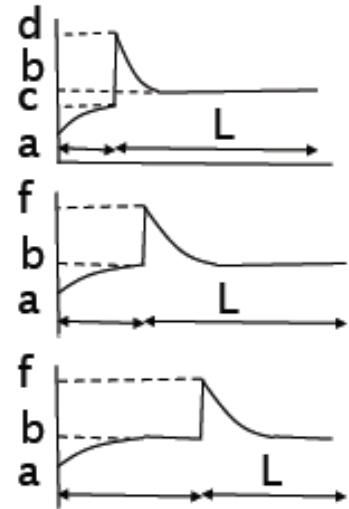
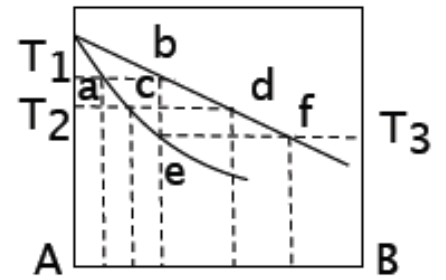


After Solidification

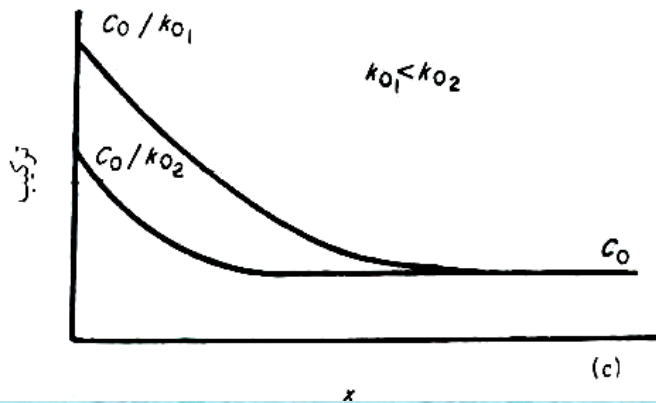
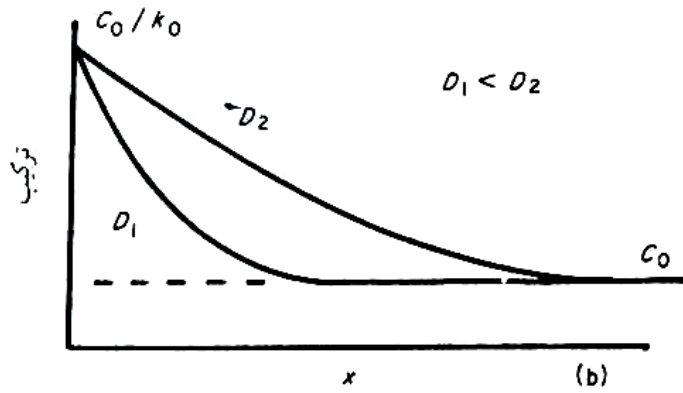
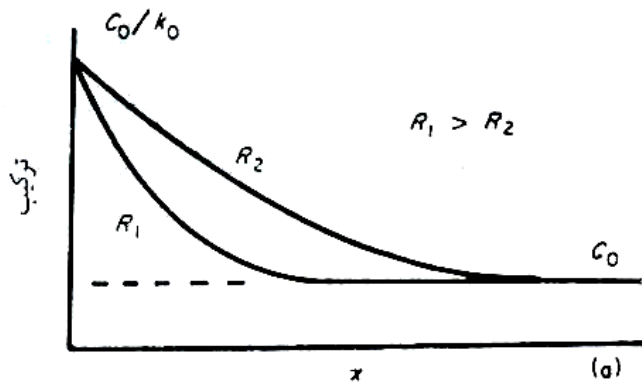


$$C_s^* = C_o \left(1 + (1-k) e^{-\frac{kx}{D/v}} \right)$$

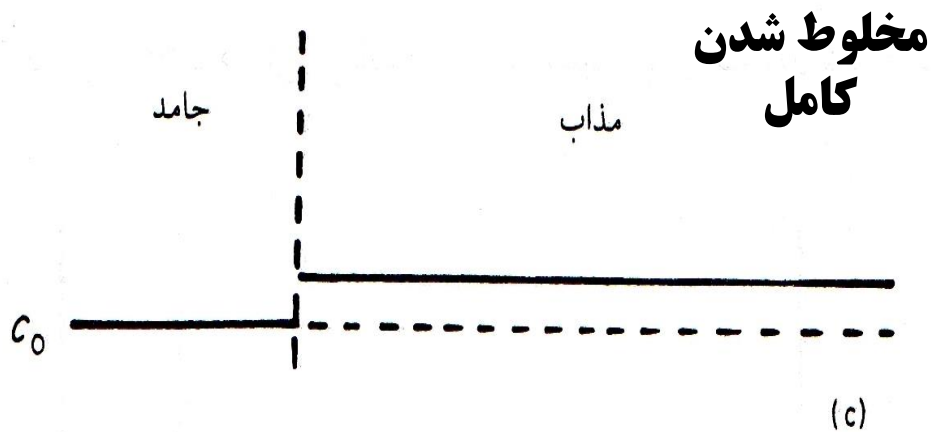
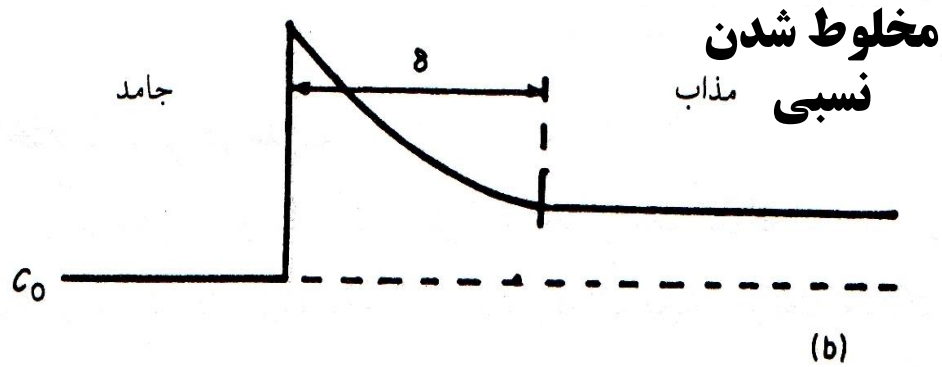
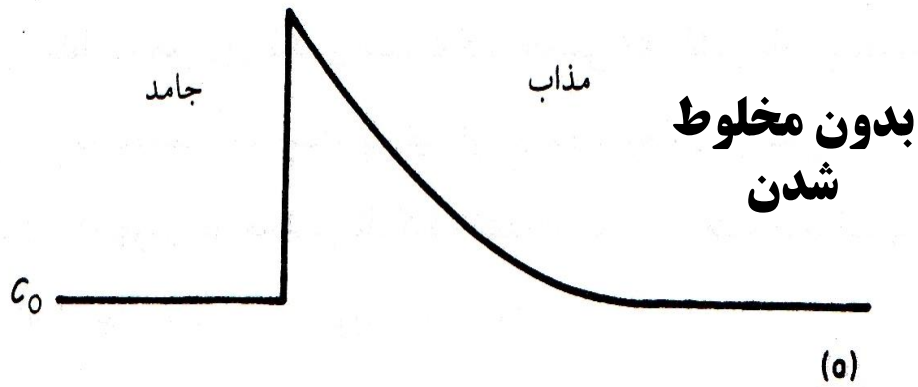
$$C_l = C_o \left(1 + \frac{1-k}{k} e^{\frac{kx}{D/v}} \right)$$



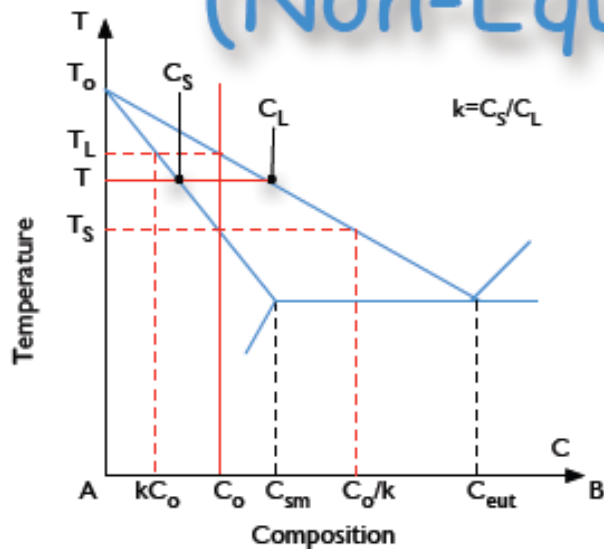
تأثیر پارامترهای مختلف بر غلظت جلوی جبهه انجماد



تأثیر هم زدن مذاب
بر روی لایه عنصر
حل شونده در فصل
مشترک



No Solid Diffusion (Non-Equilibrium Lever Rule)



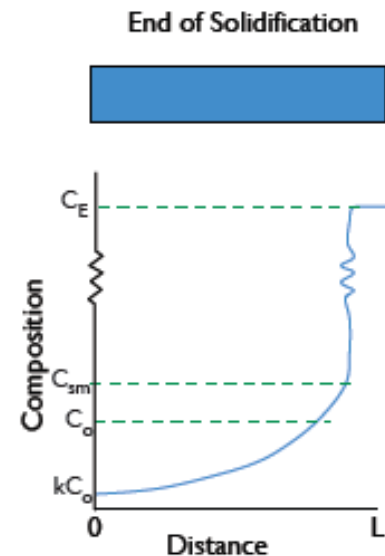
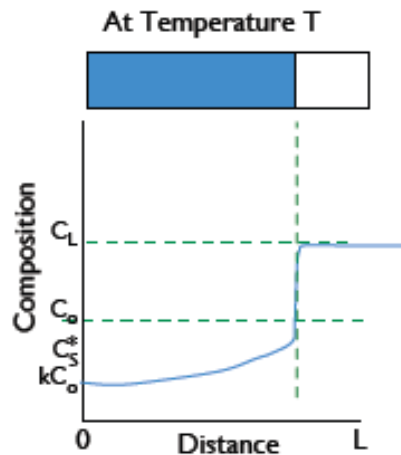
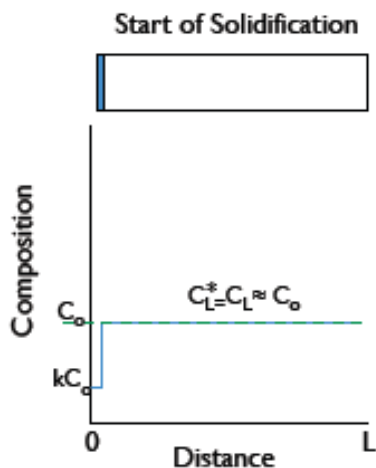
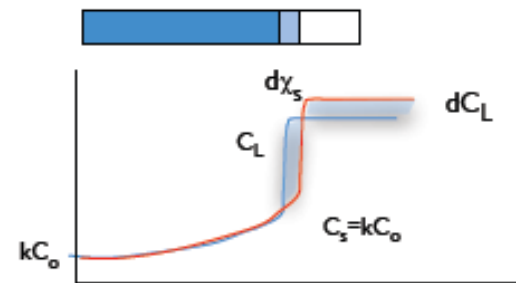
solidification of $d\chi_s$

$$(C_l - C_s^*)d\chi_s = (1 - \chi_s)dC_l$$

rejected solute from solid solute increase in liquid

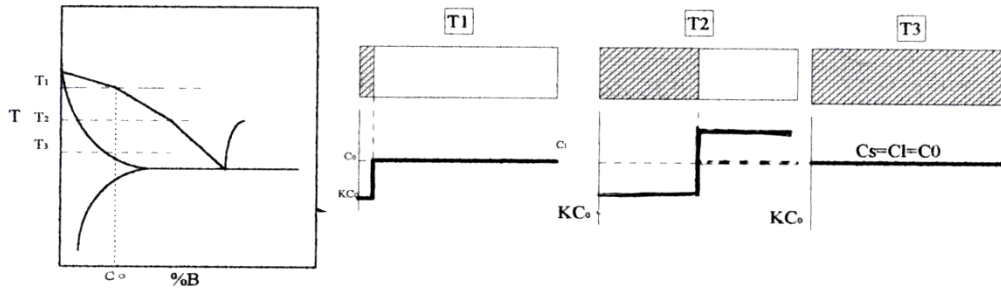
$$\int_0^{\chi_s} \frac{d\chi}{1 - \chi} = \int_{C_o}^{C_l} \frac{dC_l}{C_l(1 - k)}$$

$$C_l = C_o(1 - \chi_s)^{k-1} \quad C_s^* = kC_o(1 - \chi_s)^{k-1} \quad \text{Scheil relation}$$



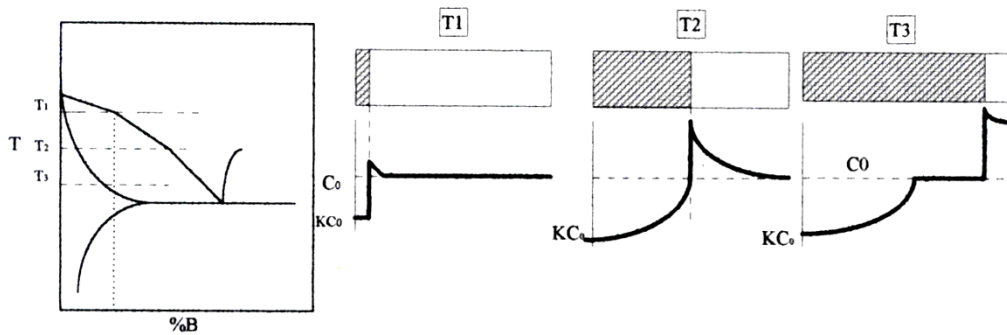
Solidification

Equilibrium state: Type I
 Diffusion in solid and liquid is complete.



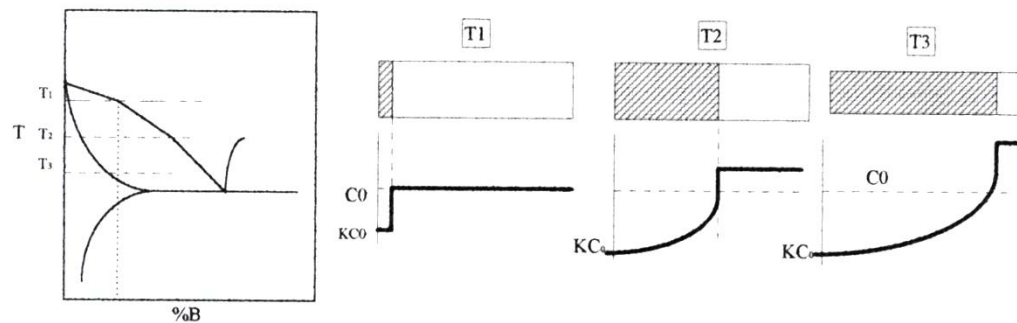
انجماد تعادلی

Non-equilibrium state: Type III



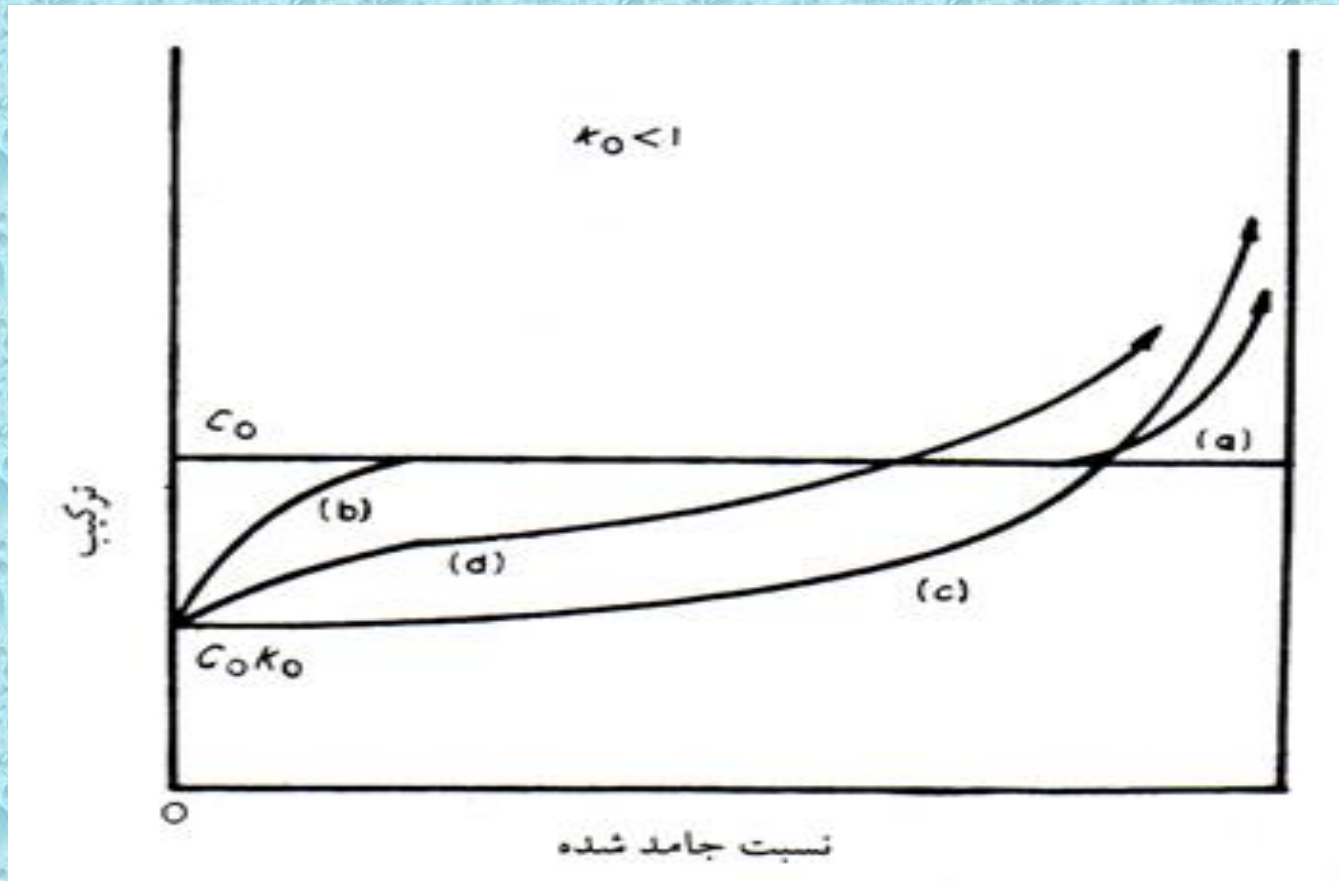
انجماد غیر تعادلی

Non-equilibrium state: Type II



**انجماد غیر تعادلی
 با همزدن مذاب**

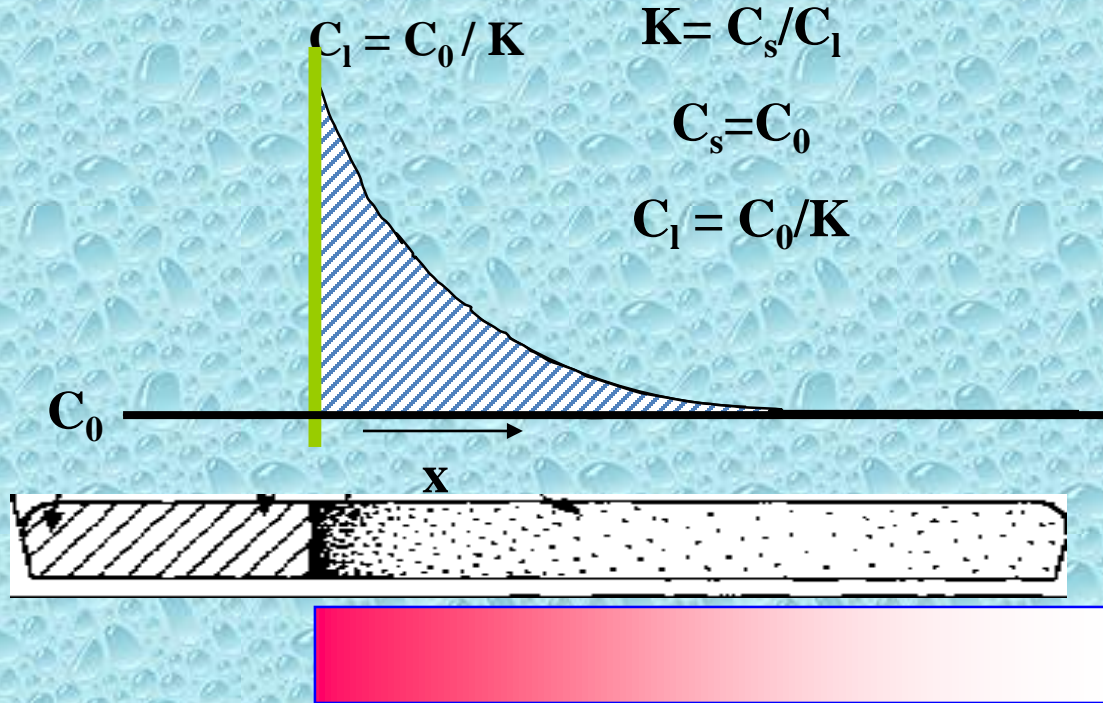
پروفیل غلظت یک شمش افقی در انواع انجماد



رشد

در بعد ماکروسکوپی

تغییرات غلظت در جلوی
جبهه انجماد در انجماد
غیر تعادلی

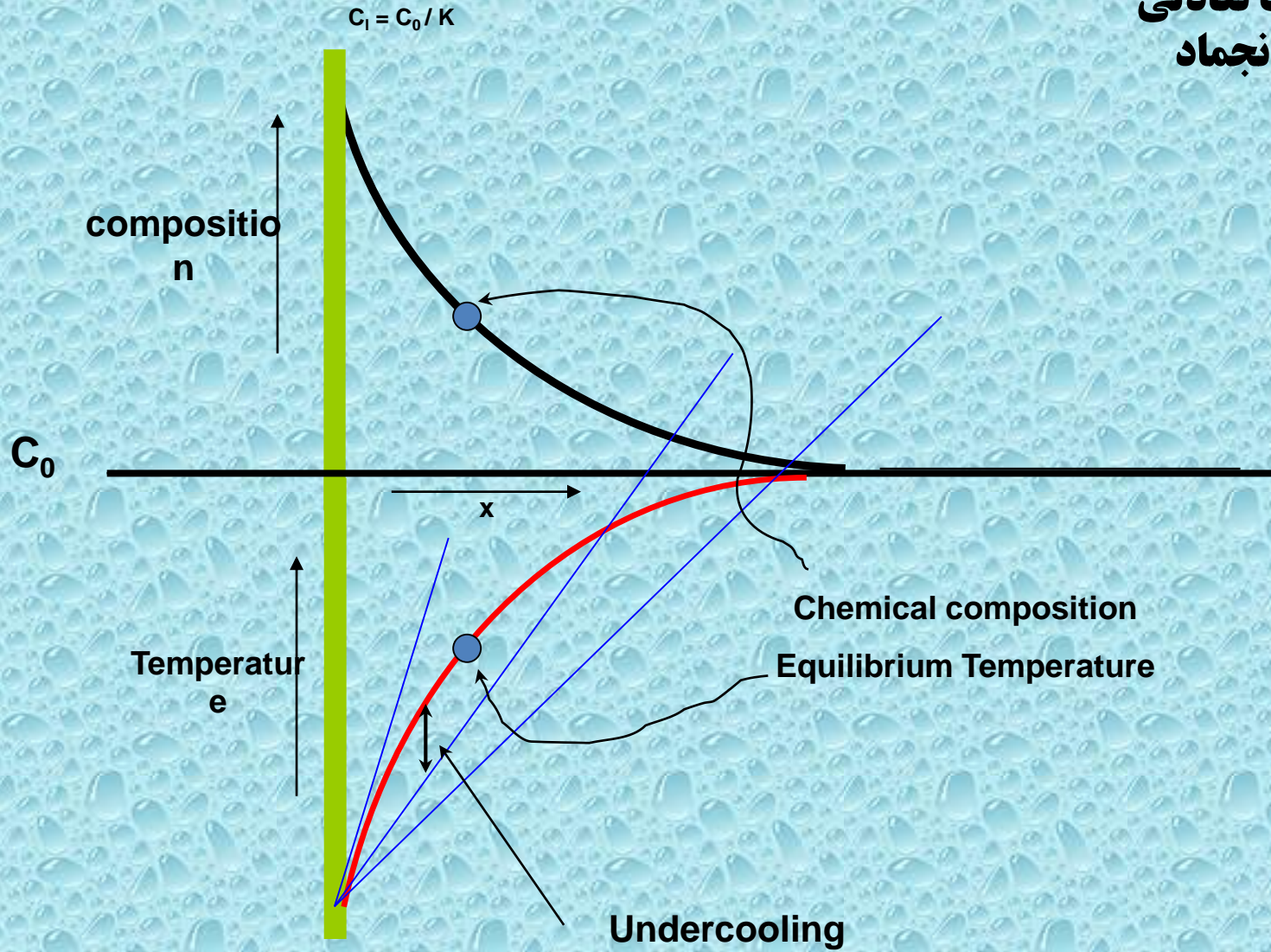


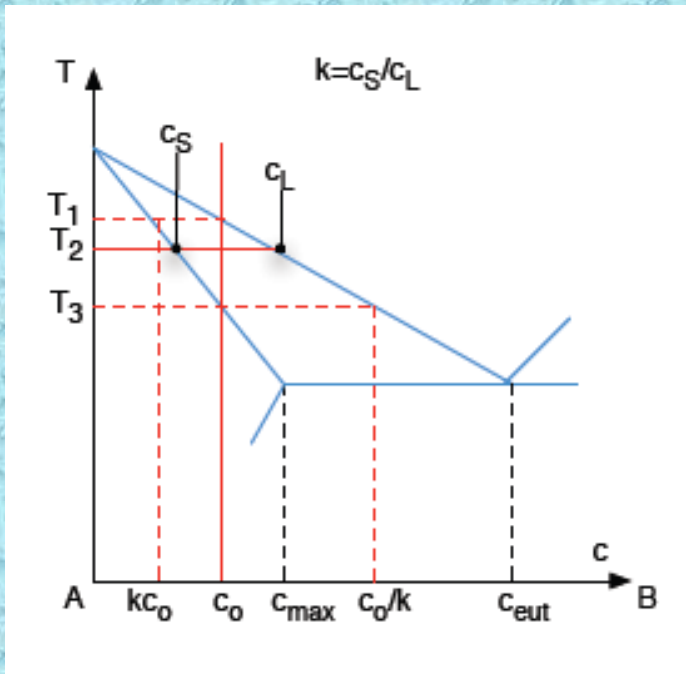
$$C = C_0 \left[1 + \frac{1 - K_0}{K_0} \exp \left(- \frac{Rx}{D} \right) \right]$$

$$T_l = T_m - mc_0 \left[1 + \frac{1 - K_0}{K_0} \exp \left(- \frac{Rx}{D} \right) \right]$$

دمای تعادلی مذاب نقاط مختلف جلوی فصل مشترک

تغییرات دمایی ذوب تعادلی در جلوی جبهه انجماد



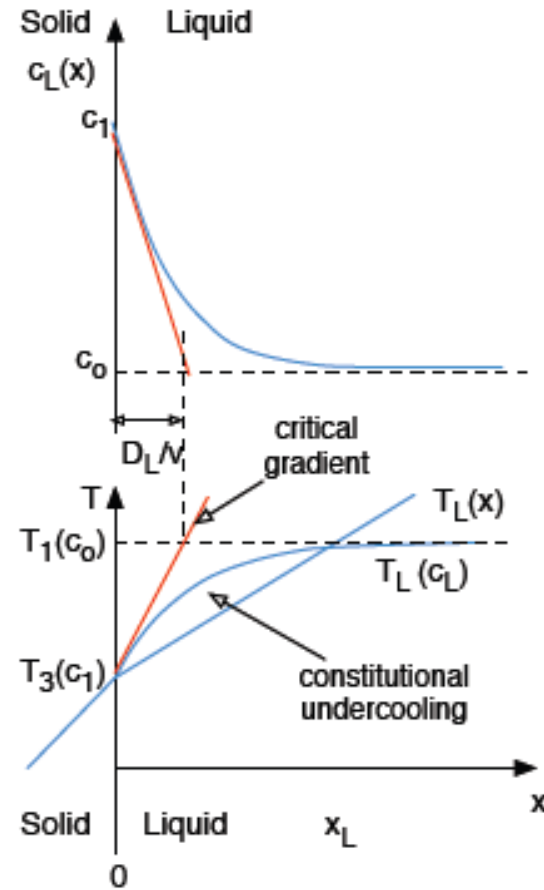


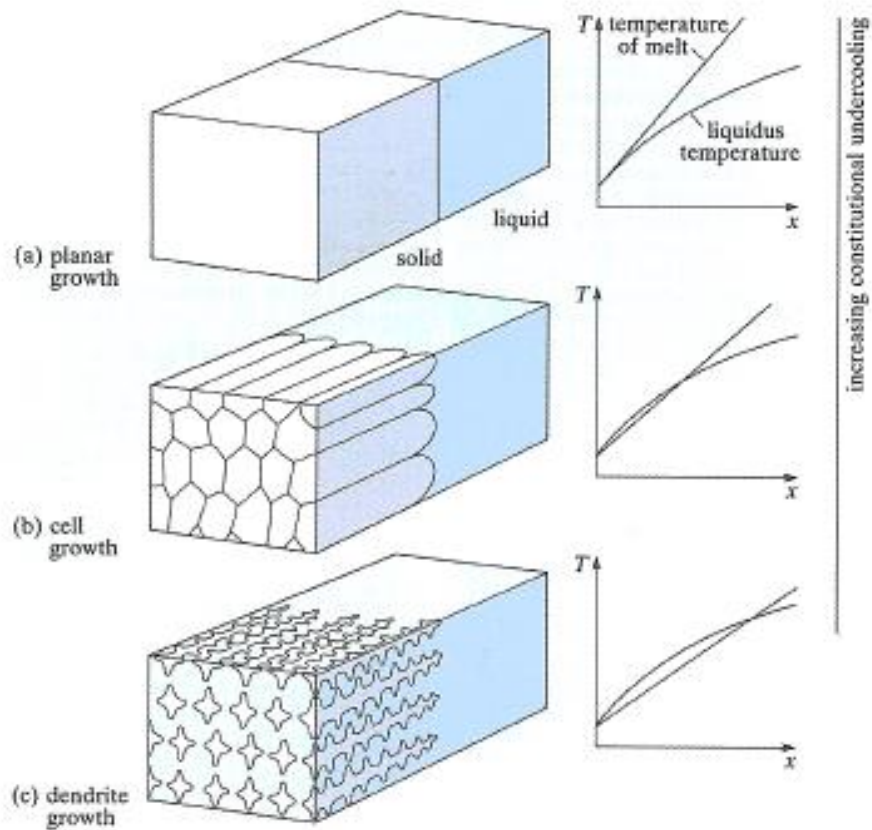
$$T_l = T_m - mc \cdot \left[1 + \frac{1 - K_s}{K_s} \exp\left(-\frac{Rx}{D}\right) \right]$$

$$G > \left(\frac{dT_l}{dx}\right)_{x=0}$$

$$\frac{G}{R} = \frac{mc}{D} \frac{1 - K_s}{K_s}$$

در نقطه مماس:





Planar growth

→ cell growth

→ dendrite growth



no undercooling

moderate undercooling

strong undercooling

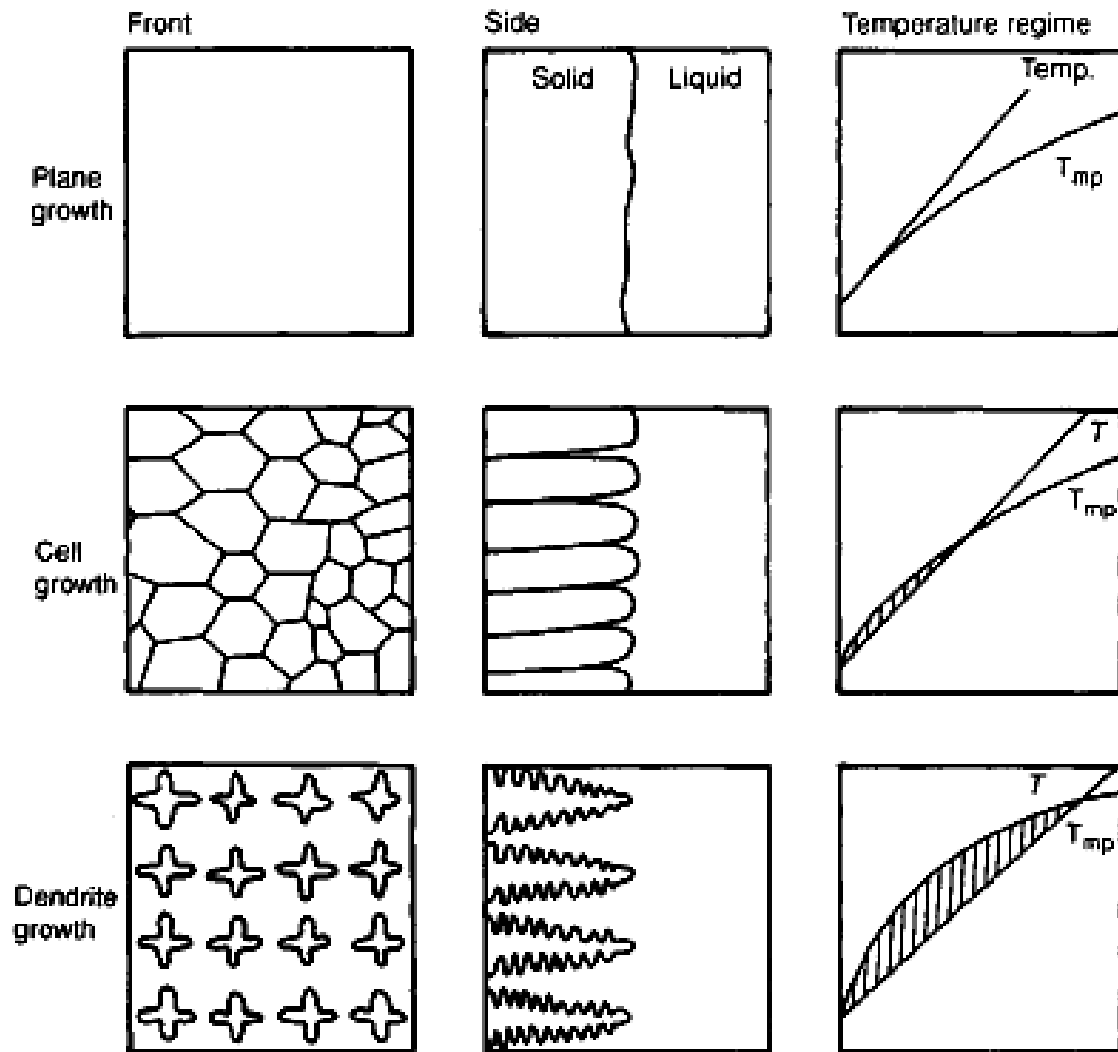
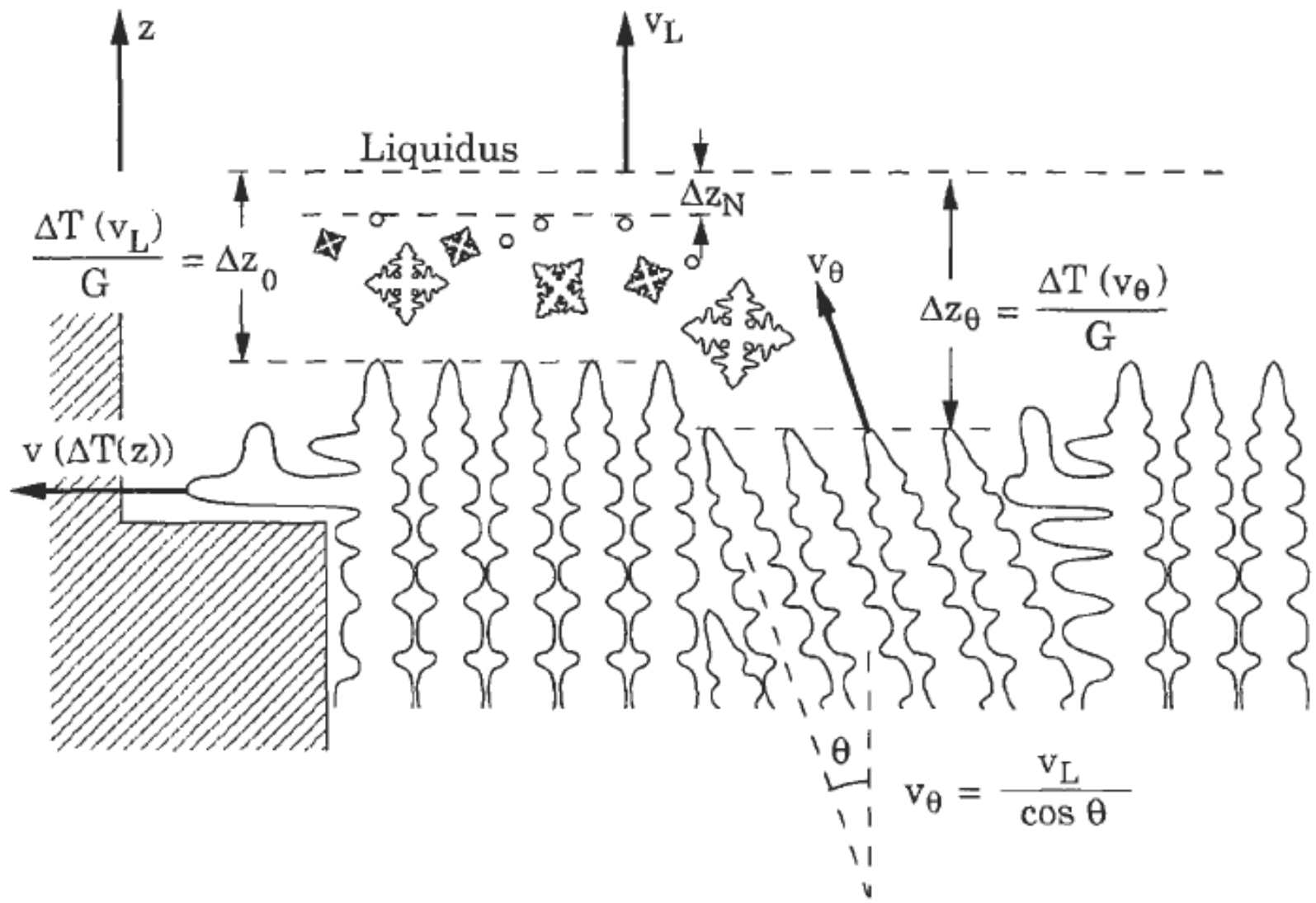


Figure 4.20 The transition of growth morphology from planar, to cellular, to dendritic, as compositionally induced undercooling increases (equivalent to G/R being reduced).





Growth Interfaces

Growth of Interfaces depends on

Concentration Gradient

Temperature Gradient

Undercooling

Growth Rate

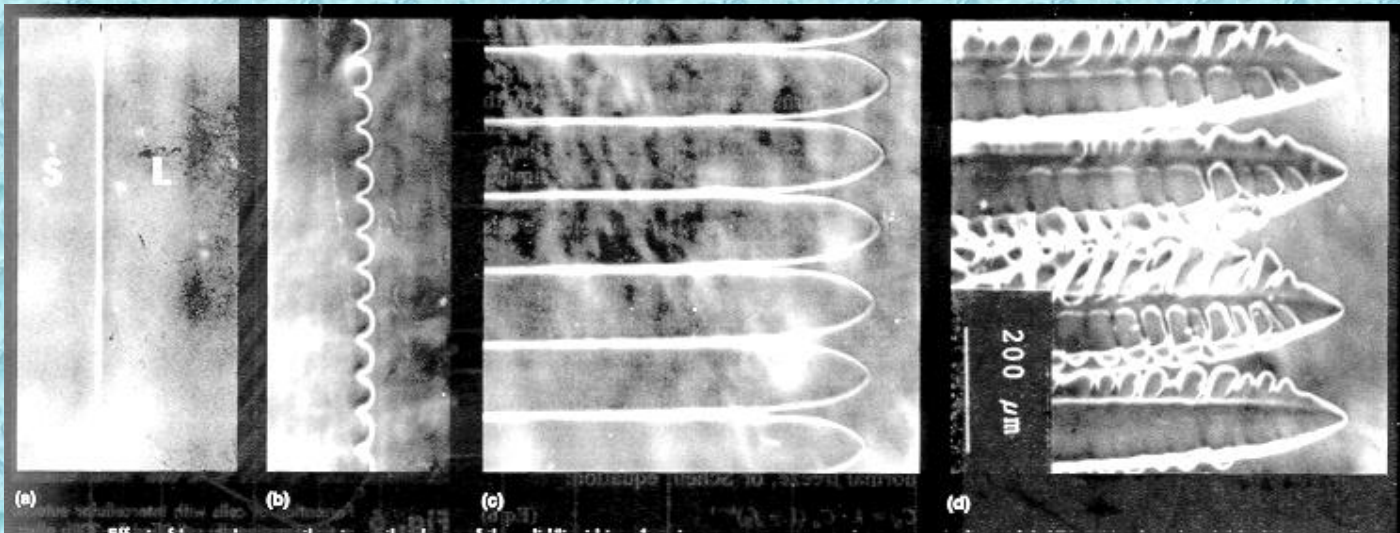
انواع رشد

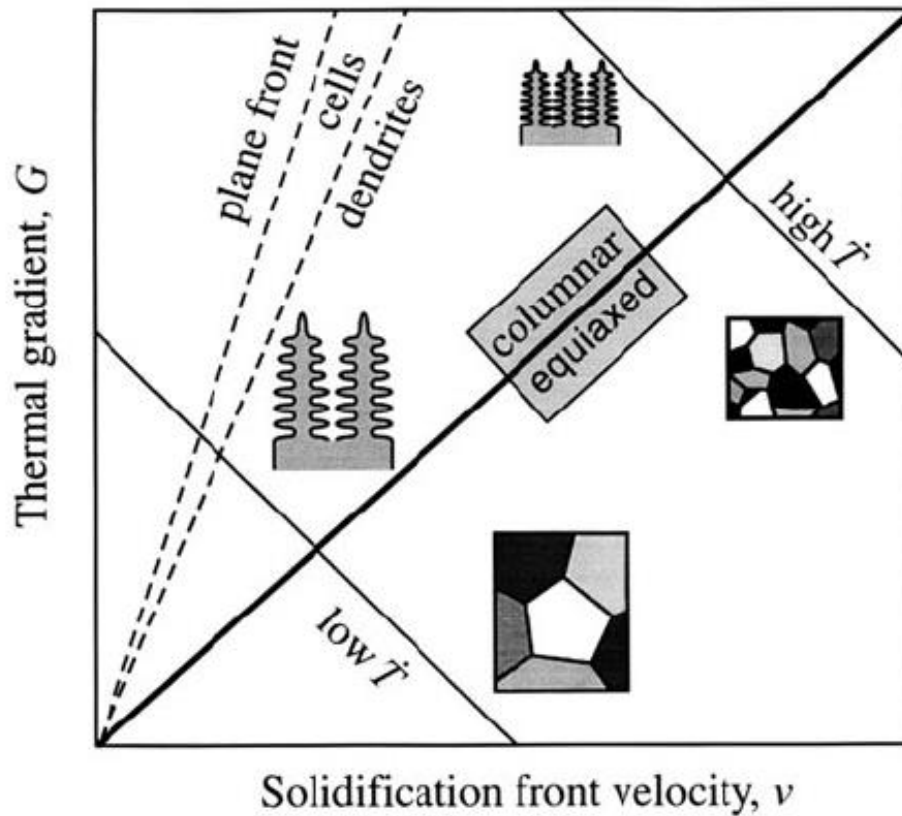
• مسطح

• سلولي (حجمي)

• دندريتي

• مستقل (محوري)





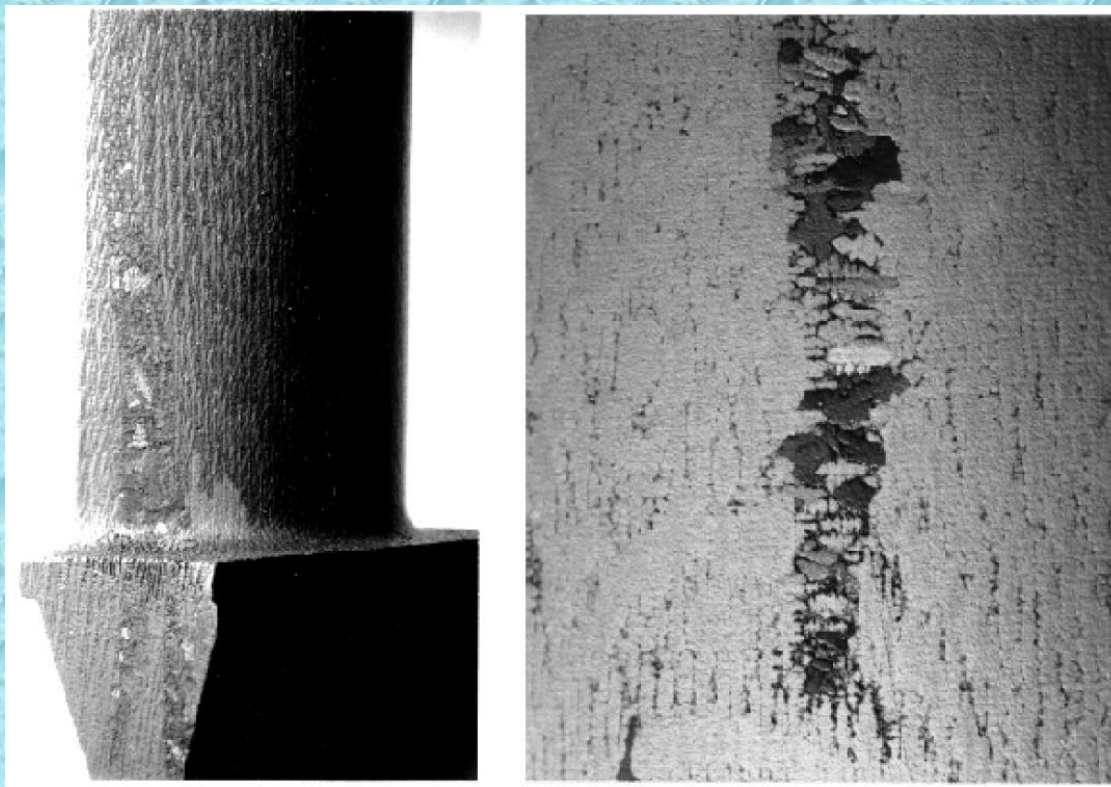
تأثیر پارامترهای مختلف بر نوع رشد فصل مشترک

$$\frac{G}{R} > \frac{mc_p}{D} \frac{1 - K_0}{K_0}$$

- (د) غلظت بالای آلیاژ T
- (ه) قابلیت نفوذ کم در مذاب
- (و) K_0 بسیار پایین برای $1 < K_0$
- (ز) K_0 بسیار بالا برای $1 > K_0$

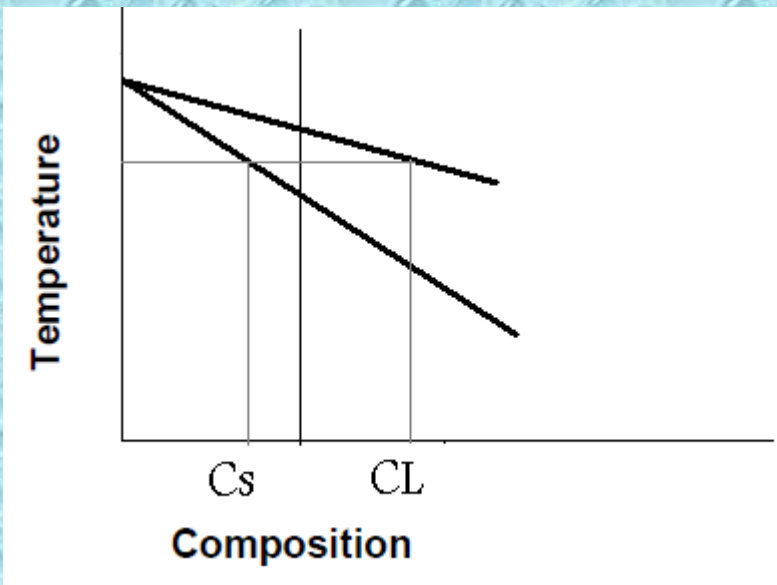
- (الف) شیب کم دما در مذاب
- (ب) سرعتهای رشد زیاد
- (ج) خطوط لیکوئیدوس با شیب تند

جدایش در انجماد

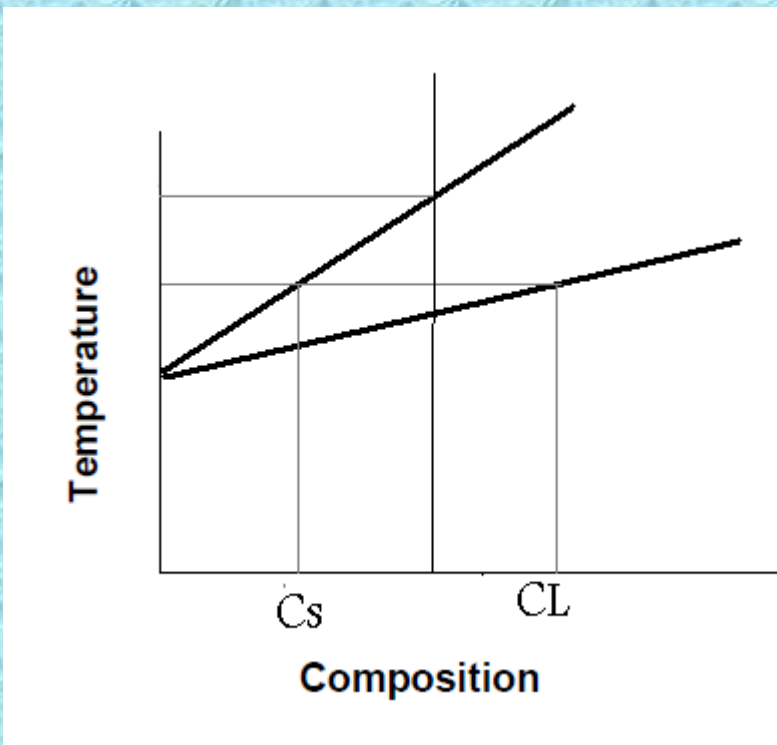


جدایش:

جدایش مستقیم (نرمال): $K < 1$

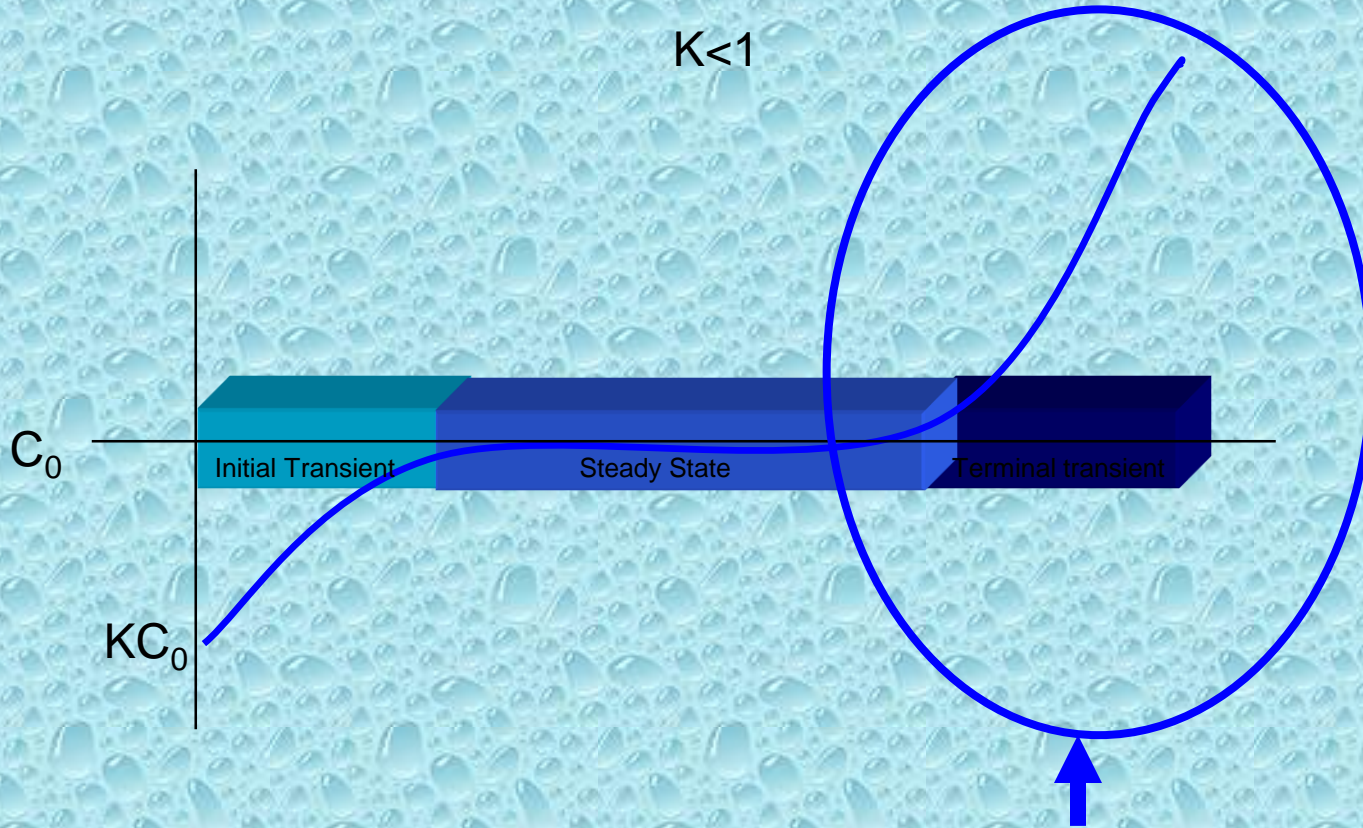


جدایش معکوس: $K > 1$



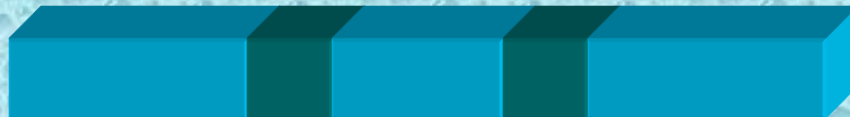
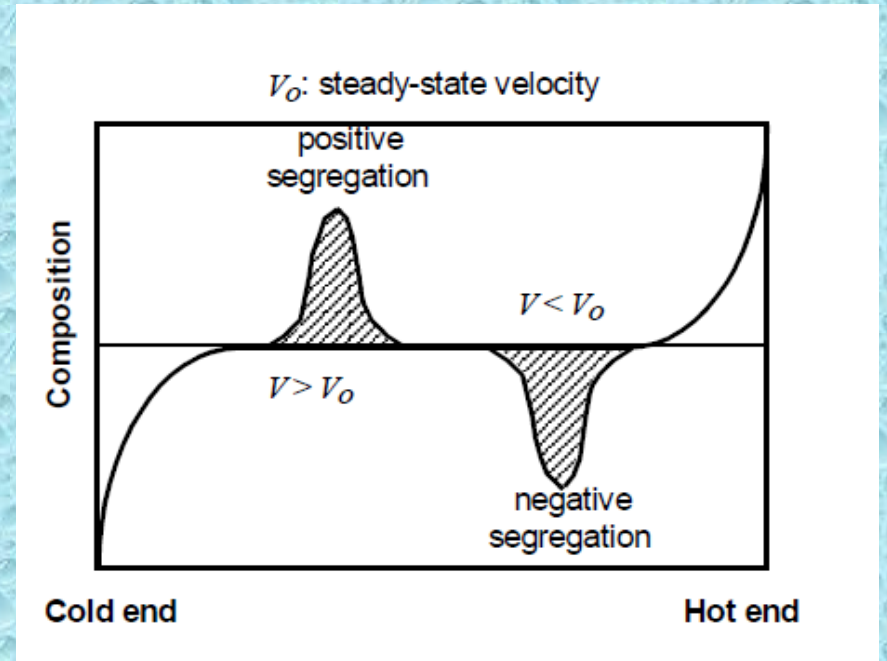
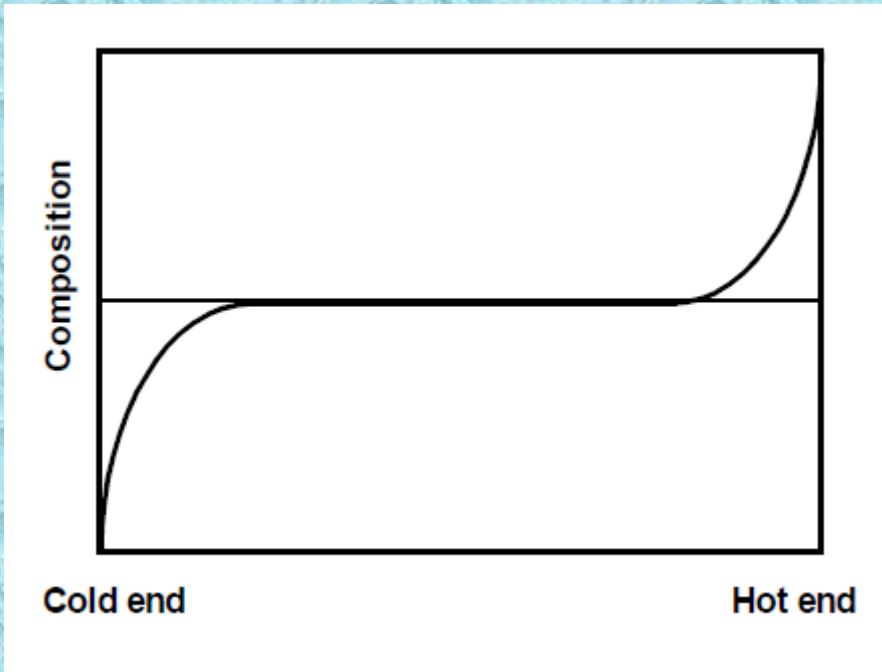
جدایش مستقیم (نرمال): $K < 1$

$K < 1$



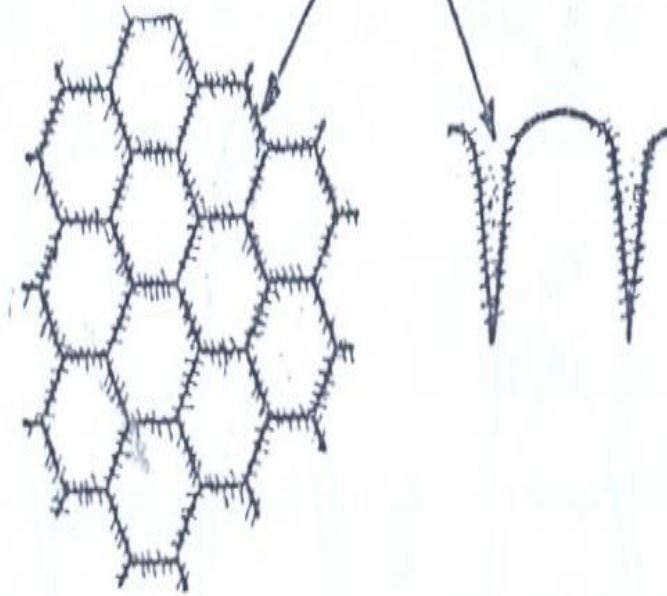
تغییر غلظت از کناره قطعه تا مرکز و تمرکز عنصر آلیاژی در مرکز

تغییر غلظت موضعی در نقاط مختلف قطعه ناشی از تغییر آهنگ انجماد و ایجاد باندینگ



جدایش سلولی یا بین سلولی

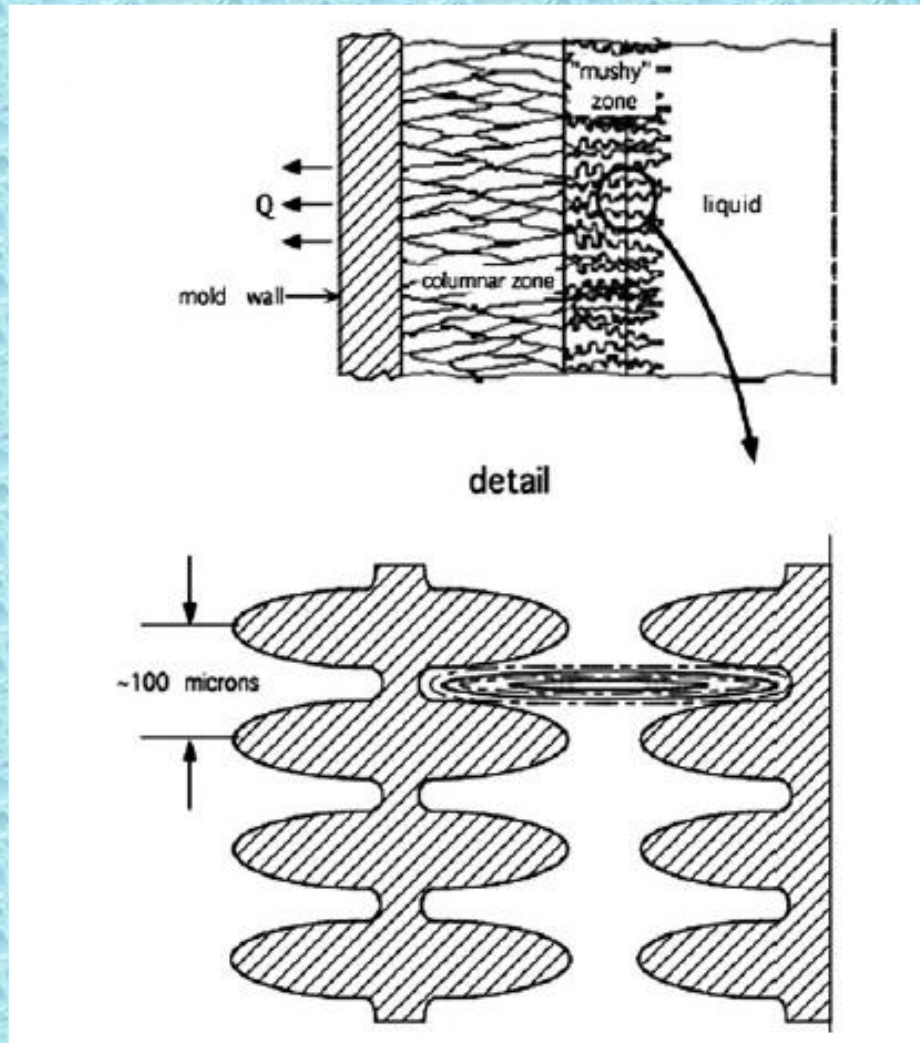
تجمع عناصر حل شونده (C) در مرزخانه‌ها



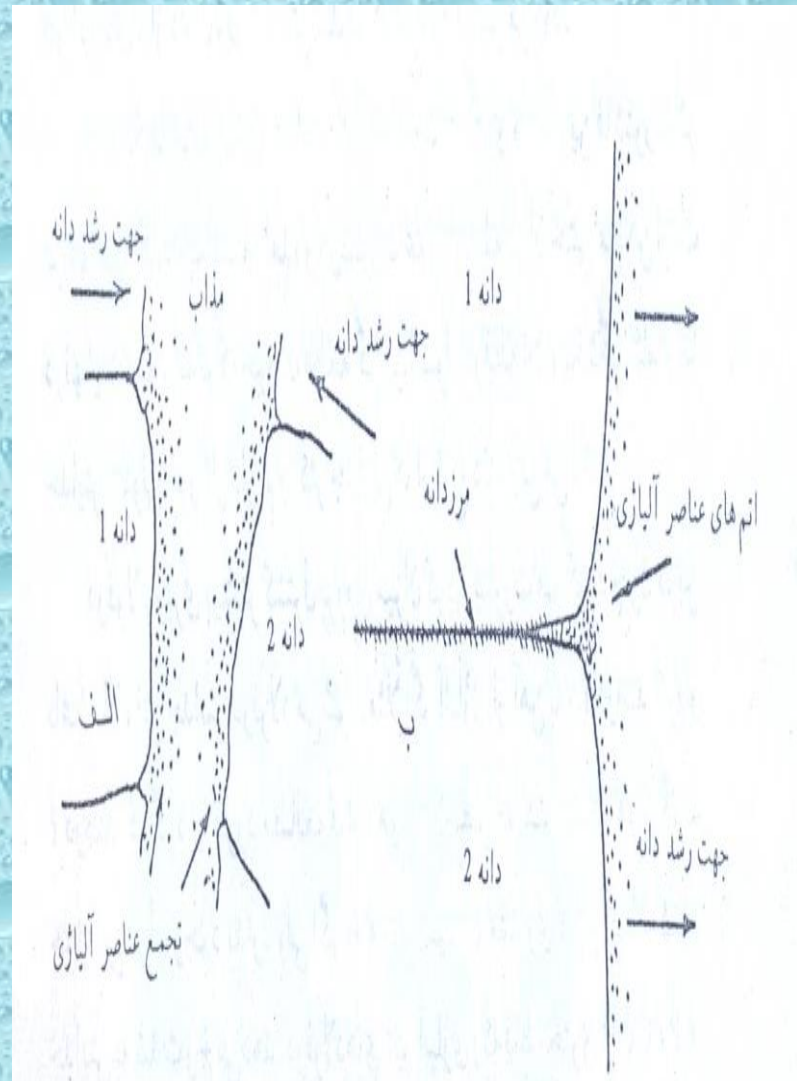
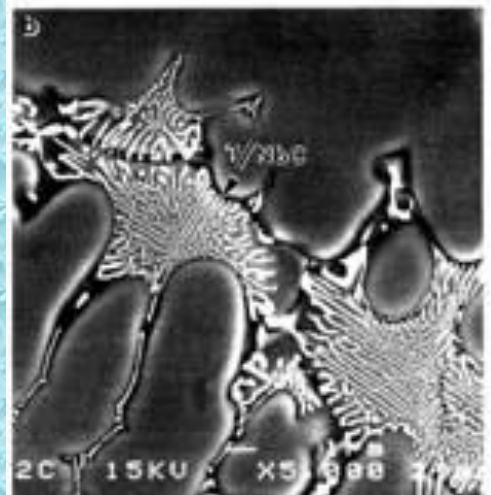
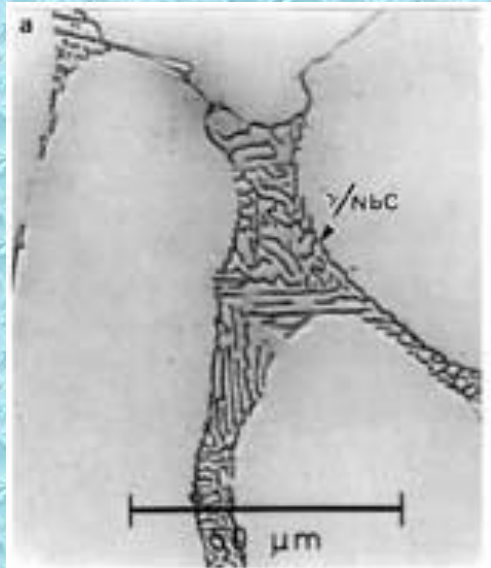
مقطع عمود بر فصل مشترک

مقطع موازی با فصل مشترک

جدایش دندریتی

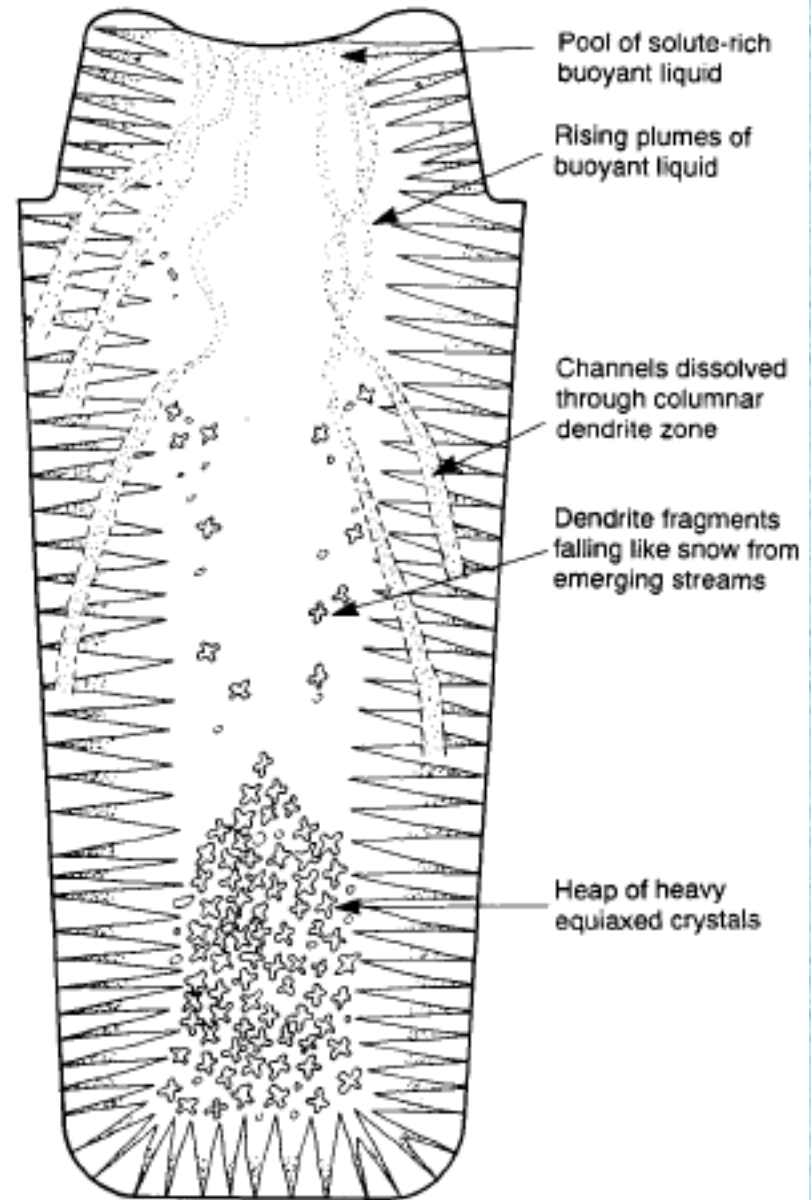


جدایش بین دانه ای



Segregation

Macrosegregation in Steel



(a) Partially solidified ingot

Segregation

Macrosegregation in Keeled Steel

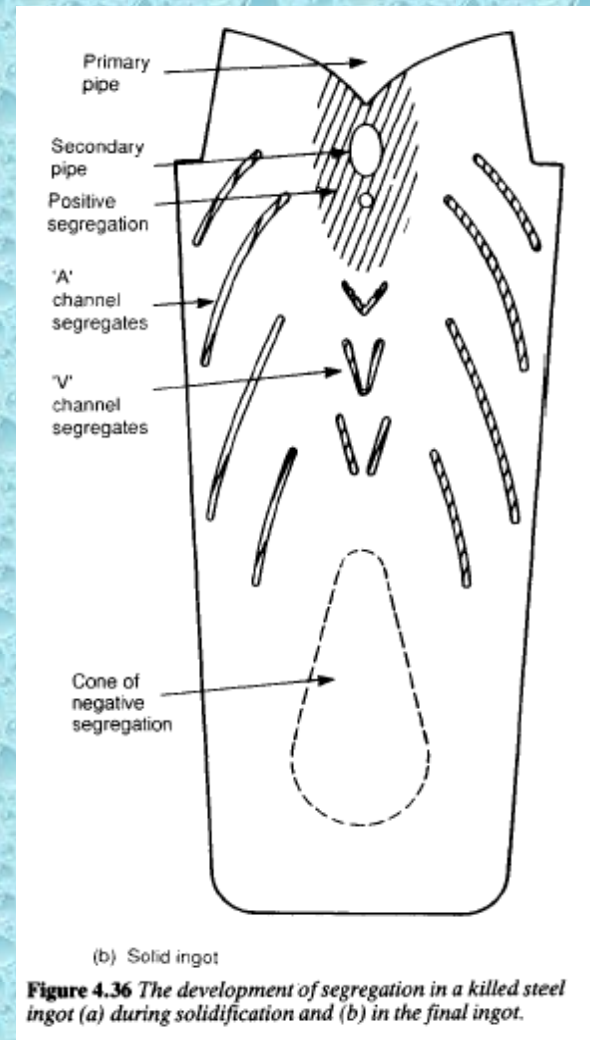
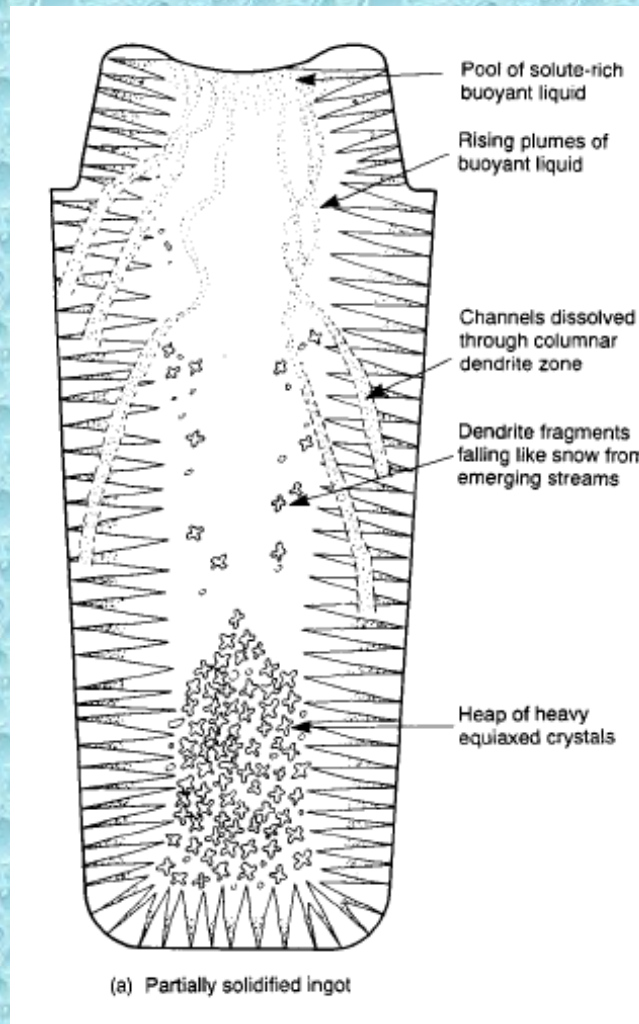
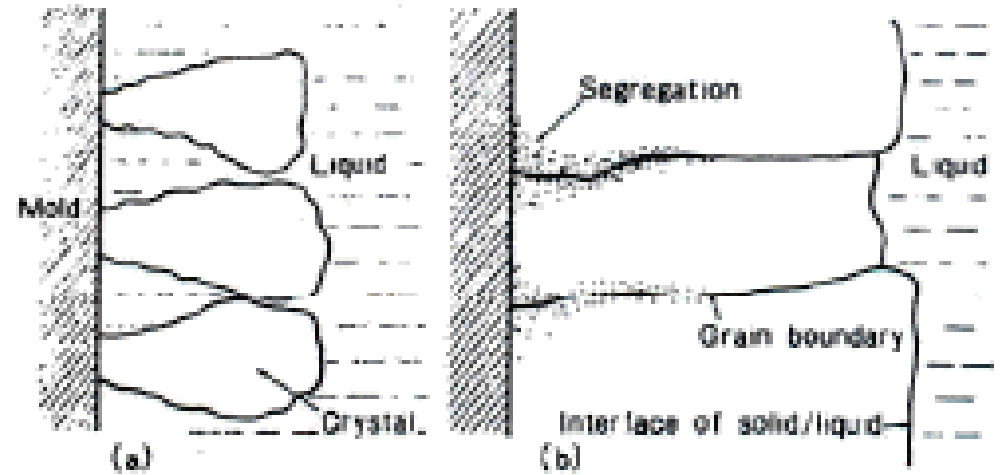
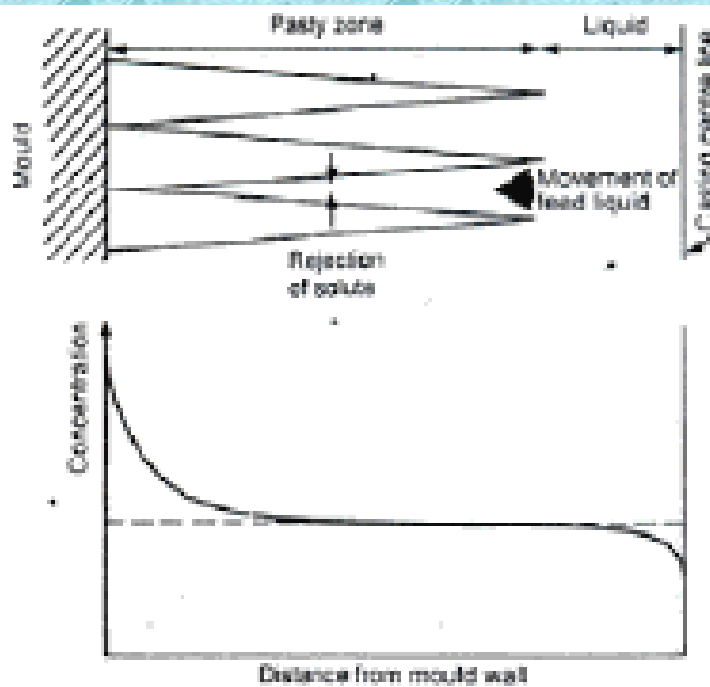
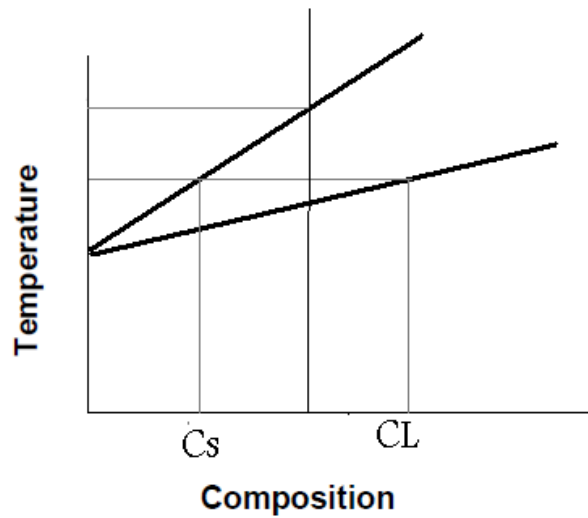


Figure 4.36 The development of segregation in a killed steel ingot (a) during solidification and (b) in the final ingot.



Sulphur print of vertical cross-section of rectangular ingot

جدایش معکوس: $K > 1$



مانند:

پدیده عرق قلع (Tin sweat)

شرایط:

$K > 1$

گاز محلول زیاد

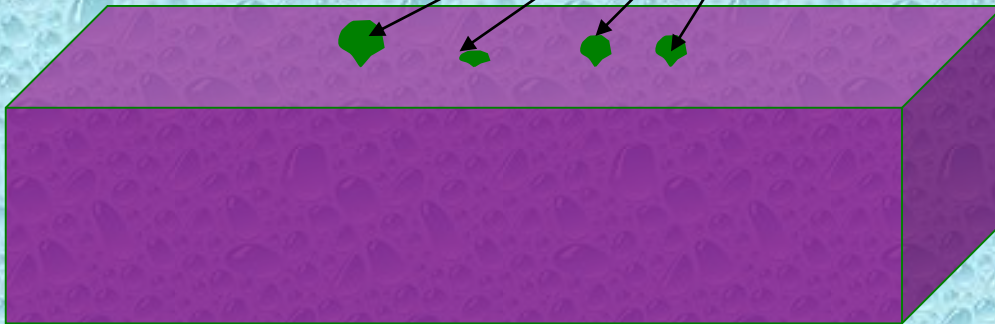
میزان انقباض زیاد

روشهای حذف پدیده:

گاز زدایی کامل

سرعت انجماد بالا

قطرات حاوی
قلع زیاد



با تشکر

در این پاورپوینت علاوه بر استفاده از کلیه منابع لاتین و فارسی موجود و نیز منابع اینترنتی، از جزوه درسی اساتید گرامی دکتر امامی: دانشگاه تهران، دکتر آشوری: دانشگاه شریف، و دکتر شبستری: دانشگاه علم و صنعت نیز استفاده گردیده است.