Answer:

a) The desired difference Δy is given by equation 10.
b) The condition for competitive growth is $\Delta y \geq \lambda$.

-

6.7 Macrostructures in Cast Materials

Eutectic growth and dendrite growth has been discussed earlier in this chapter. Eutectic growth is a special case of solidification as it occurs only in alloys with eutectic composition.

The solidification occurs in the majority of alloys and in pure metals by aid of *unidirectional dendrite growth of nucleated crystals in the metal melts.* This fact has been known for more than a century and will be applied on solidification processes of metal melts after casting.

Background

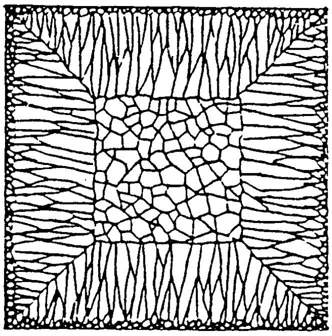


Figure 36.

At the end of the 19th century the Russian metallurgist Tschernoff published an epoch-making report concerning the solidification of steel ingots. He performed a detailed study of the crystal shapes of both the uncovered crystals he found in the shrinkage cavities in steel ingots and the crystals tightly grown together, which he could observe in a microscope.

He found that the macrostructure of a steel ingot could be divided into three distinct zones.

- a surface zone with small crystals of approximately equal size, *the surface crystal zone*
- a zone with long columnar crystals, *the columnar zone*
- a zone in the centre with relatively large, equiaxed crystals, *the equiaxed crystal zone.*

The production of large steel ingots, which could be forged and rolled, started in the middle of the 19th century, when new steel processes like the Bessemer and Martin processes were developed. The knowledge of the metal structure was very diffuse. Since then much research on the structure of metals at solidification has resulted in greatly improved casting methods and properties of the final products.

Macrostructures of Unidirectionally Cast Materials

Tschernoff´s observations have later been confirmed experimentally in many ways. They are the basis of the modern conception of the macrostructure of cast metals.

If we look with a naked eye at the crystals in a macroetched sample we can see the *macrostructure,* i. e. the surface zone, the columnar zone and the central zone. The crystal region in the columnar zone has increased according to the mechanism described in example 5 on page 48 and in figure 37.

In the columnar zone smaller and larger single crystals of different shapes, sizes and random orientation can be observed (figure 37). They are equiaxed crystals of the same kind as the ones in the central zone. Their origin will be discussed on pages 57-58.

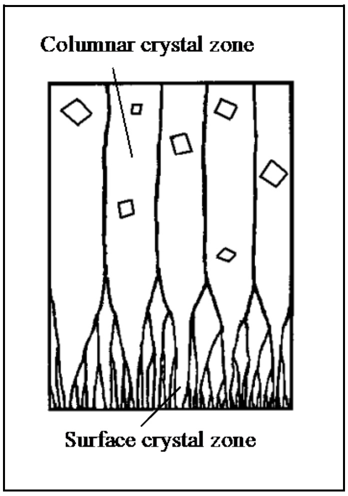


Figure 37.

The three basic zones occur in the final products at all types of casting processes. Below experimental evidence of the influence of various parameters, which influence the macrostructure, will be shortly discussed. The formation of each of the three zones will then be discussed separately in the sections 6.7.1, 6.7.2 respectively 6.7.3.

Influence of Casting Temperature and other Parameters on the Crystal Structure

During modern time much work has been done to explain the influence of various factors on the casting structure. The Swedish metallurgist Hultgren´s row of publications, starting in the 1920th, constitutes a milestone within this field. The research has then continued during the whole of the 20th century and is still going on.

Hultgren showed that it is possible to vary the length of the columnar crystals by varying the casting temperature. An increase of the casting temperature leads to an increase of the columnar zone at the expense of the central zone (figure 38 a). A decrease of the casting temperature gives the structure, illustrated in figure 38 b. At *low* temperature the columnar zone may be completely absent (figure 38 c).

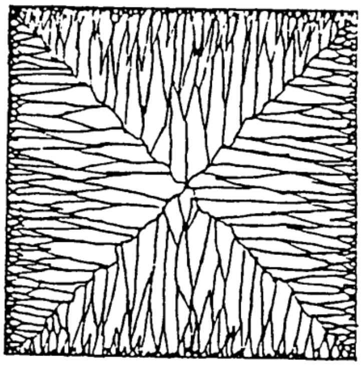


Figure 38 a.
Principle sketch of the macro-structure of the surface zone and the columnar zone in an ingot.

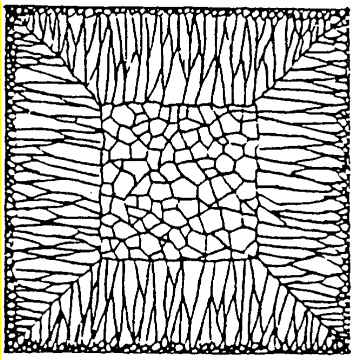


Figure 38 b.
Principle sketch of the macro-structure of the surface zone, the columnar zone and the equiaxed zone in the centre of an ingot.

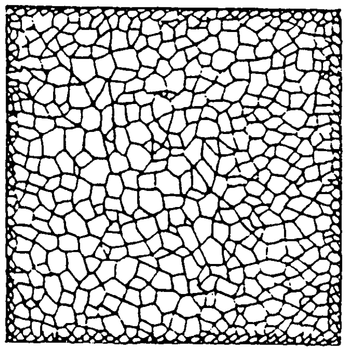


Figure 38 c.
Principle sketch of the macro-structure of an ingot.The equiaxed zone has grown at the expense of the columnar zone.

Hultgren also found that the structure was influenced by other factors like stirring the melt during solidification, slow tapping into the mould and refilling during solidification. It has been found later that the structure in a similar way can be changed due to the properties of the mould, by addition of small amounts of foreign elements and by change of the composition of the alloy.

Experience shows that the surface crystal region is always small, while the shapes and relative sizes of the columnar and central zones vary considerably, depending on factors like

- casting temperature of the melt
- casting method
- growth rate
- cooling rate.

Table 2 characterises roughly the most common casting methods and relates the macrostructure of the metal to some of the most important factors listed on next page. The temperature distribution in the melt, solidified metal and mould results in the characteristic features of the different casting methods. Variation is achieved by change of cooling conditions.

Table 2. Influence of some parameters on the macrostructure of castings.

Casting method	Cooling Rate	Growth Rate	Columnar Zone	Macro-structure
Continuous casting	very strong	high	long	Figure 38 a
Ingot casting	strong	medium	short	Figure 38 b
Sand mould	weak	slow	absent	Figure 38 c

6.7.1 Formation of the Surface Crystal Zone

At permanent mould casting processes the melt is cast in close contact with a metal/mould surface, which has room temperature or may be water-cooled. The melt is rapidly cooled to the critical temperature T^* required for nucleation. A large number of nucleated randomly oriented small crystals are formed. The temperature gradient in the melt favours crystal growth in the direction of grad T (example 5, page 48) at the bottom surface. The structure is called the *surface crystal zone*.

We assume that the temperature distribution in the melt is given by the curve 1 in figure 39 when the first nucleus of solid phase is formed. The surface of this growing crystal is initially small, which means that the generated solidification heat per unit time is small even if the growth rate is high. This amount is not enough to balance the amount of heat which is carried away by cooling and the temperature in the melt decreases, which is illustrated by curve 2 in figure 39.

Several nuclei may be formed, even within the very farthest layer. When the nuclei have become many enough and have got a sufficiently large total surface the generated solidification heat becomes so large that it balances more than enough the amount of heat carried away by cooling, if this one is not too strong. The temperature of the strongly undercooled zone increases and the temperature conditions are illustrated in curve 3 in figure 39. No new nuclei are formed.

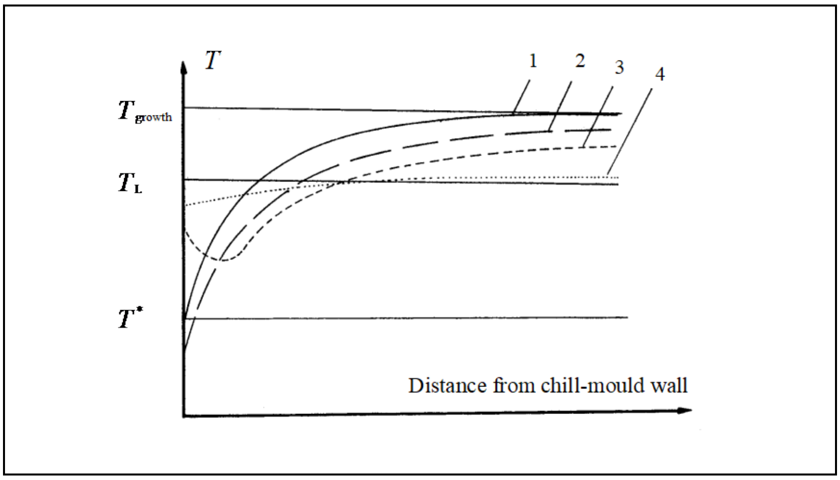


Figure 39.
Temperature distribution in a metal melt at the initial stage of solidification as a function of time – one curve for each value of the time.

The temperature of the melt increases until the growth rate of the formed nuclei has decreased so much that the solidification heat balances the outer cooling and a relatively homogenous temperature of the melt is obtained – curve 4 in figure 39.

6.7.2 Formation of the Columnar Crystal Zone

The whole initial solidification process occurs in connection with the growth of the nuclei of solid phase to crystal skeletons, dendrites. It has been shown that part of these crystal skeletons will be broken by the strong convection, which is always present in the melt immediately after the casting. For this reason a strong crystal multiplication appears in certain cases, which contribute considerably to the increase of the number of nuclei in the surface zone.

The reasoning above shows that formation of many nuclei is to be expected during the initial stage of the solidification. These nuclei constitute the origin of the so-called surface crystal zone, which often is rather fine-grained. After this initial stage the formation of nuclei normally ceases, which is caused by an increase of the temperature, as the curves 3 and 4 in figure 39 show.

The continued solidification occurs almost entirely by growth of already nucleated crystals. Due to competitive growth the crystals grow in the direction of the temperature gradient, i. e. inwards from the surface zone, towards the centre of the melt. Each crystal consists of several parallel primary dendrite arms, all of which have grown equally far into the melt. Dendrites are initially formed by growth of arms and branches in certain crystallographic directions. During a later stage these arms grow together and form distinct planes.

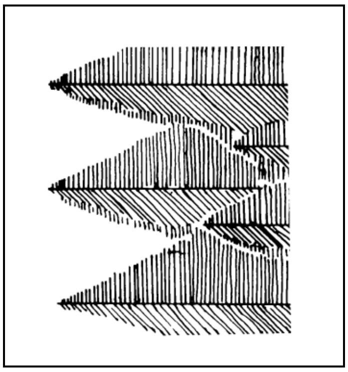


Figure 40.
Parallel primary dendrite arms, which grow inwards in the melt, form together a columnar crystal.
The three dendrite arms lie in the same horizontal plane.

By making a cut through a columnar crystal from the surface and inwards, towards the centre, one has been able to follow the extension of the individual dendrite crystals. Figure 40 shows a principle sketch of a columnar crystal.

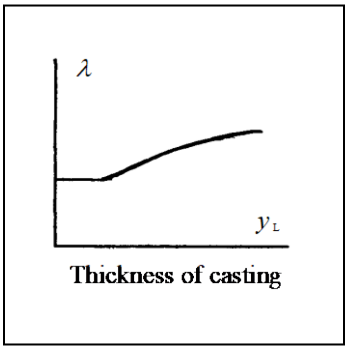
As a consequence of the decrease of the growth rate at the solidification front with the distance from the surface of the casting, the distance between the dendrite tips increases according to the relation (9) on page 12

$$v_{\text{growth}} \cdot \lambda^2 = \text{const} \tag{9}$$

When the growth rate decreases the structure becomes coarser which is evident from figure 43 and 45 on pages 63 respectively 64.

Example 6.

In a foundry the dendrite arm distance of unidirectionally cast Al castings was studied as a function of the thickness of the casting. The measurements from the surface of the casting and inwards were plotted in a diagram.



It was found that the dendrite arm distance was constant as a function of the casting thickness up to a certain critical thick-ness. The dendrite arm distance then increased parabolically with the thickness. Explain these results.

Solution and Answer:

The heat transport through the solidifying shell controls the growth rate, which in its turn controls the dendrite arm distance according to the relation

$$v_{\text{growth}} \cdot \lambda^2 = \text{const} \tag{1'}$$

which means that

$$\lambda = \frac{\text{const}}{\sqrt{v_{\text{growth}}}} \tag{2'}$$

We use the general expression of the solidification rate from equation (46) on page 34 in chapter 4:

$$v_{\text{growth}} = \frac{\mathrm{d}y_{\mathrm{L}}}{\mathrm{d}t} = \frac{T_{\mathrm{L}} - T_{\mathrm{o}}}{\rho(-\Delta H)} \cdot \frac{h}{1 + \dfrac{h}{k} \cdot y_{\mathrm{L}}} \tag{3'}$$

Case I: Thin castings, i. e. Nussel´s number $\mathrm{Nu} = \frac{h}{k} \cdot y_{\mathrm{L}} << 1$

The term $\frac{h}{k} \cdot y_{\mathrm{L}}$ can be neglected in comparison with 1 and equation (3´) can be reduced to

$$v_{\text{growth}} = \frac{\mathrm{d}y_{\mathrm{L}}}{\mathrm{d}t} = \frac{T_{\mathrm{L}} - T_{\mathrm{o}}}{\rho(-\Delta H)} \cdot h \tag{4'}$$

i.e. v_{growth} is constant. Consequently the dendrite arm distance is also constant at thin castings in agreement with the experimental results.

Case II: Thick castings, i. e. Nussel´s number is not small compared to 1.

In this case equation (3´) can be written

$$v_{\text{growth}} = \frac{\mathrm{d}y_{\mathrm{L}}}{\mathrm{d}t} = \frac{T_{\mathrm{L}} - T_{\mathrm{o}}}{\rho(-\Delta H)} \cdot \frac{h}{1 + \dfrac{h}{k} \cdot y_{\mathrm{L}}} \tag{5'}$$

and we get

$$\lambda = \frac{\text{const}}{\sqrt{\dfrac{\mathrm{d}y_{\mathrm{L}}}{\mathrm{d}t}}} = \text{Const} \cdot \sqrt{1 + \frac{h}{k} \cdot y_{\mathrm{L}}} \tag{6'}$$

When $\frac{h}{k} \cdot y_L >> 1$ the relation (6′) can be written

$$\lambda = Const \cdot \sqrt{y_L} \qquad (7')$$

i.e. the dendrite arm distance increases parabolically with the casting thickness in agreement with the experimental results.

6.7.3 Formation of the Central Crystal Zone. Equiaxed Crystals of Random Orientation

Tschernoff was the first one, who discussed the formation of equiaxed crystals and a central zone, in the scientific literature. His observations on ingots have been confirmed by microscopic studies and other convincing experimental evidence.

The crystals have a random orientation – all directions are equally frequent. The proper technical term to describe these crystals is *equiaxed crystals of random orientation*.

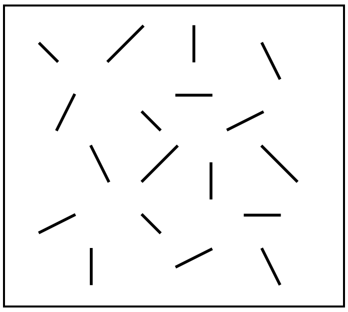


Figure 41.
Equiaxed crystals in the central zone, orientated at random.

The fact that the crystals have various orientations when they precipitate from the melt shows that they are formed from separate nuclei. Sometimes during the precipitation process these crystals have floated freely in the melt. They are designa-ted as free or freely floating crystals in the melt at this stage.

Studies of the solidification process, based on rapid cooling while the reaction is going on, show that these crystals, which float freely in the melt, can grow to a considerable size.

Formation of Equiaxed Crystals of Random Orientation

There are several different theories of the nucleation of freely floating crystals. The theories have been applied on ingots below but are valid for other types of castings as well.

One theory is that new nuclei are formed by *crystal multiplication* within the melt. This process has been discussed earlier in section 6.3.3 on page 13. Both Hultgren and Southin have showed that there are crystals in the central zone, which partly have the same structure as the crystals at the upper surface of the ingot. The explanation of this may be that dendrite fragments from the solid metal layer at the upper surface can be torn off, due to convection in the melt, and serve as heterogeneities for nucleation of equiaxed crystals in the central zone.

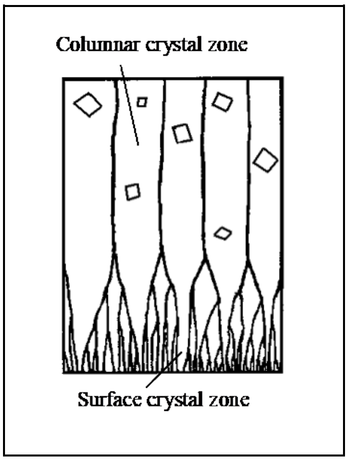


Figure 37.

Of course it is not necessary that crystal fragments get torn off particularly from the upper surface of the ingot. It may happen all over the ingot where the proper conditions for fractures of the crystal arms are available.

Another theory, presented by Howe, is that the concentration of segregated elements ahead of the solidification front may cause *undercooling of the melt* with the consequence that new crystals form at the lower temperature. Hultgren penetrated this theory. He claimed that an undercooled zone may appear, due to the diffusion in front of the solidification front, and that nucleation of new equiaxed crystals, ahead of the front, may occur there.

Figure 42 shows how such an undercooled zone may arise. The left part of the figure shows the concentration profile of alloying elements in the melt in front of a growing dendrite tip.

The right part of the figure shows how this profile can be transformed to a curve, which describes how the temperature must vary theoretically, to cause every point in the melt to be at

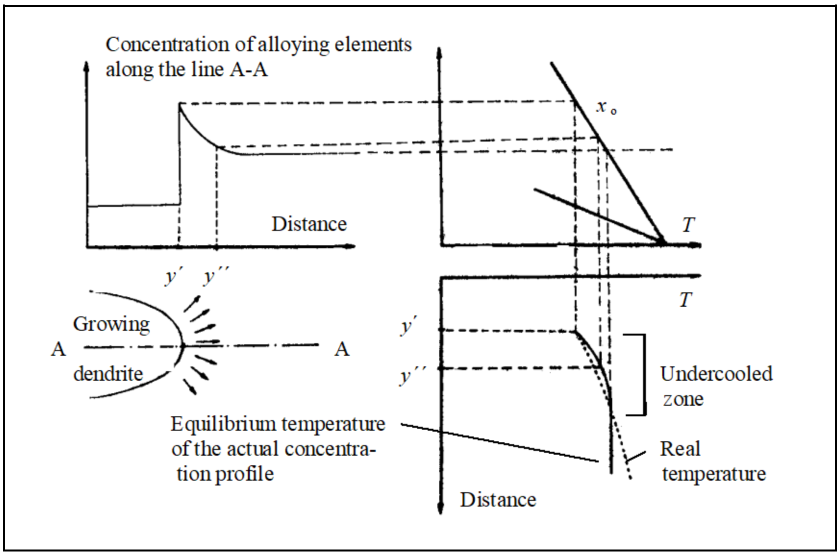


Figure 42.
Formation of an undercooled zone in front of a growing dendrite tip in a metal.

the liquidus temperature, the highest temperature at which solid phase can exist in the melt. If the real temperature profile is shallow enough, an undercooled zone may arise, which is the condition for formation of freely floating crystals.

In many cases a lot of impurities are present in the melt and new euiaxed crystals can easily be formed by inoculation. In addition, the number of growing crystals can be increased by crystal multiplication, enhanced by convection in the melt.

Formation of the Central Zone

When the number of freely floating crystals is large enough and the growing crystals have grown to a certain critical size they will effectively block the further growth of the columnar crystals. Then the central zone will replace the columnar zone.

However, there will be no growth of the new crystals and no zone change unless the released heat of formation is transported away. As an example this matter will be discussed for ingots on page 67.

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Example 7.

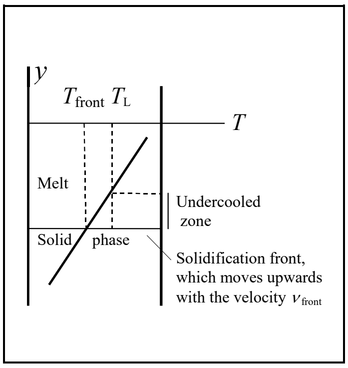
Find the relation between the relative withdrawal velocity and the temperature gradient, which must be valid in an equipment of controlled unidirectional solidification, if a sudden change from columnar crystals to equiaxed crystals of random orientation is to be avoided in a stellite alloy with the following properties:

1 The growth rate of an object is proportional to the tempera-ture difference between the liquidus temperature and the tem-perature of the melt close to the growing object

$$v_{\text{growth}} = 10^{-4} \cdot (T_{\text{L}} - T) \quad \text{m/s}$$

2 The primary dendrite distance is described by the relation

$$v_{\text{growth}} \cdot \lambda^2 = 10^{-12} \quad \text{m}^3/\text{s}$$



Solution:

We have two growing objects: the solidification front and a nucleated crystal, which grows somewhere in the undercooled zone.

The solidification front moves *upwards* with the growth rate v_{front}, relative to the casting. Simultaneously the whole casting is moved *downwards* with the same velocity. The result is that the solidification front remains at rest, relative to the surroundings.

Thus the withdrawal velocity has the same magnitude as v_{front} but opposite direction.

Motion of the Solidification Front:

We apply the condition 1 in the text on the solidification front of growing dendrites, where $T = T_{\text{front}}$, and get

$$\frac{\mathrm{d}y}{\mathrm{d}t} = v_{\text{front}} = 10^{-4} \cdot (T_L - T_{\text{front}}) \qquad (1')$$

The temperature gradient close to solidification front is

$$|\text{grad}\, T| = \frac{\mathrm{d}T}{\mathrm{d}y} \qquad (2')$$

Equation (2′) is multiplied by v_{front}, which is equal to dy/dt :

$$v_{\text{front}} \cdot |\text{grad}\, T| = \frac{\mathrm{d}y}{\mathrm{d}t} \cdot \frac{\mathrm{d}T}{\mathrm{d}y} = \frac{\mathrm{d}T}{\mathrm{d}t} \qquad (3')$$

Equation (3′) can be integrated. We want t_{max}, the time it takes for the solidification front to move (relative to the casting) from the position where $T = T_{\text{front}}$ to the position where $T = T_L$.

Both v_{front} and grad T are constant, which gives

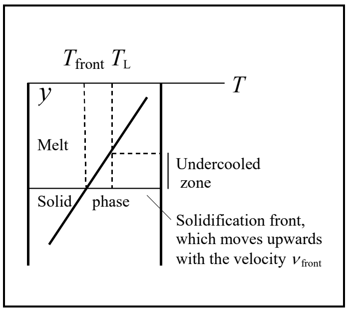
$$v_{\text{front}} \cdot |\text{grad}\, T| \cdot \int_0^{t_{\text{max}}} \mathrm{d}t = \int_{T_{\text{front}}}^{T_L} \mathrm{d}T$$ or, by aid of equation (1′):

$$t_{\text{max}} = \frac{T_L - T_{\text{front}}}{v_{\text{front}} \cdot |\text{grad}\, T|} = \frac{10^4}{|\text{grad}\, T|} \qquad (4')$$

Growth of Equiaxed Crystals

Next we will calculate the *maximum size of a growing equiaxed crystal*, which has been nucleated and grown in the undercooled zone of the melt.

Provided that the critical temperature $T^* \approx T_L$ we get the maximum size of the crystal if it is nucleated at the upper end of the undercooled zone, where the temperature is T_L at $t = 0$. Then the temperature close to the crystal decreases when the casting is moved downwards and the crystal grows until it meets the solidification front. The growth temperature $T_{crystal}$ sinks linearly from T_L to T_{front}.



The crystal growth follows the law in the text

$$\frac{dr}{dt} = v_{crystal} = 10^{-4} \cdot (T_L - T_{crystal}) \quad \text{which gives}$$

$$dr = 10^{-4} \cdot (T_L - T_{crystal}) \cdot dt \qquad (5')$$

At $t = 0$ $T = T_L$ and $T_L - T = 0$
At $t = t$ $T = T_{crystal}$ and $T_L - T = T_L - T_{crystal}$
At $t = t_{max}$ $T = T_{front}$ and $T_L - T = T_L - T_{front}$

which gives

$$\frac{t_{max}}{t} = \frac{T_L - T_{front}}{T_L - T_{crystal}} \quad \text{or} \quad T_L - T_{crystal} = \frac{T_L - T_{front}}{t_{max}} \cdot t \qquad (6')$$

This expression of $T_L - T_{crystal}$ is inserted into equation (5′):

$$dr = 10^{-4} \cdot \frac{T_L - T_{front}}{t_{max}} \cdot t\, dt$$

Equation (7′) is integrated:

$$\int_0^{r_{max}} dr = 10^{-4} \cdot \frac{T_L - T_{front}}{t_{max}} \cdot \int_0^{t_{max}} t\, dt$$

which gives

$$r_{max} = 10^{-4} \cdot \frac{T_L - T_{front}}{t_{max}} \cdot \frac{t_{max}^2}{2} \qquad (7')$$

The value of t_{max} in equation (4′) is introduced into equation (7′)

$$r_{max} = 10^{-4} \cdot \frac{T_L - T_{front}}{2} \cdot \frac{10^4}{|\text{grad}\, T|} \qquad (8')$$

By aid of equation (1) we get

$$r_{max} = \frac{v_{front} \cdot 10^4}{2 \cdot |\text{grad}\, T|} \qquad (9')$$

To avoid a sudden change from columnar crystals to equiaxed crystals of random orientation the following condition must be fulfilled (compare text and figure at the bottom of page 49):

$$r_{max} < \lambda \qquad (10')$$

Condition 2 in the text gives $\frac{v_{front} \cdot 10^4}{2 \cdot |\text{grad}\, T|} < \sqrt{\frac{10^{-12}}{v_{crystal}}}$

If we assume that the growth rate $v_{crystal}$ equals the withdrawal velocity $|v_{withdrawal}| = |v_{front}|$ we get the answer given below (in reality $v_{crystal}$ is somewhat lower. See Exercise 6-8c.)

Answer: The desired relation is $|\text{grad}\, T| > \frac{10^{10}}{2} \cdot |v_{withdrawal}|^{\frac{3}{2}}$.

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Time for Change from Columnar Zone to Central Zone during the Solidification Process

General expressions for the time of the zone change and the length of the columnar zones can not be found as the heat flux through the solid shell varies with the casting method and the shapes and sizes of the castings. An example of such calculations is given in section 6.8 on page 67 for ingots when the convection in the melt is taken into account.

6.8 Macrostructures in Ingot Cast Materials

In section 6.7 a general discussion of the macrostructure in castings has been given. In this and the following two sections some additional specific properties of the macrostructures of materials, cast by aid of the main cast house methods, will be discussed.