

solidification of the alloy Sn-10%Pb. Concentration of alloying element (Pb) in the different parts of the casting after complete solidification. When the densities in the two-phase region are *lower* than in the melt, a *high positive* macrosegregation in the *lower* part of the casting is obtained. The per cent figures represent the Pb-concentrations.

Space Experiments

Experiments on solidification in space in absence of gravitation have been performed at the beginning of the 1990th. By reduction or elimination of the gravitation force the convection was strongly reduced and macrosegregation could be avoided.

11.9 Macroseggregations in Steel Ingots

In steel ingots many different types of macroseggregations appear. Figure 48 shows a survey of macrostructures and types of macroseggregations of general occurrence.

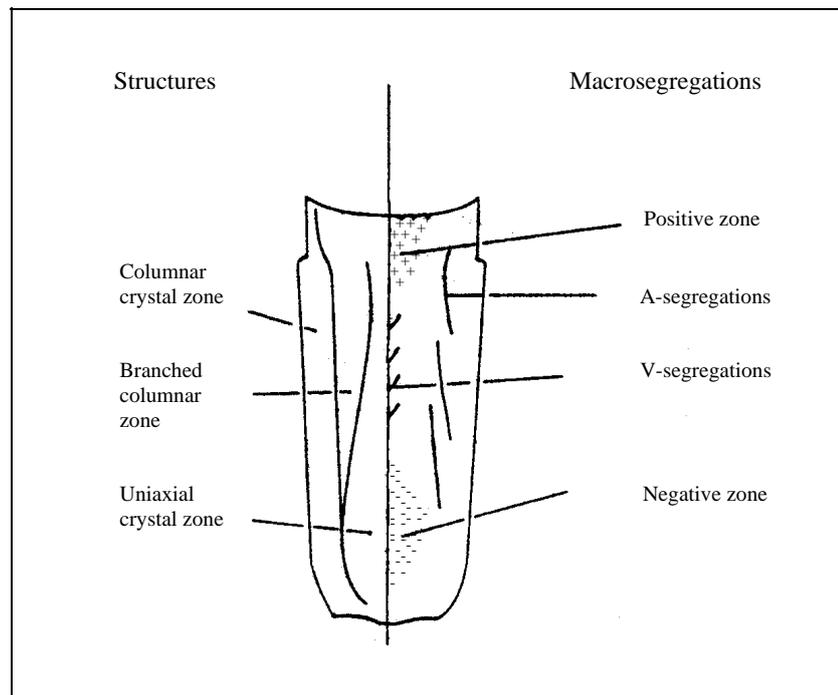


Figure 48. Survey of the structures and types of macrosegregations which often occur in ingots.

Positive segregation means that the concentration of the alloying element exceeds the average concentration. At *negative segregation* there is instead a lack of the alloying element.

The figure shows that there is an increased concentration of the alloying element at the top and more pure material at the bottom of the ingot. The left part of the figure shows that the ingot has a zone of uniaxial crystals and that this zone is located at the bottom of the ingot. As we will see in section 11.9.1 positive and negative macrosegregations have their causes in sedimentation of big crystals in the melt during the solidification process.

The right part of figure 48 shows that so-called A-segregates occur. They can be described as pencil-like channels filled with steel, which contain high concentrations of the alloying elements. In the centre of the ingot there are in addition V-segregates. These are of the same shapes and types, which are present in continuously cast strands. The V-segregates will be discussed more in detail later in section 11.9.3.

11.9.1 Macrosegregation at Sedimentation

Small crystals keep floating in a melt due to the thermal motion, mainly by convection, which is considerable in a metal melt. The crystals grow dendritically by continuous solidification of melt, which get caught at their dendrite arms. When a crystal has reached a certain critical size the thermal motion can no longer compensate the gravitation force minus the buoyancy force and the crystal sinks towards the bottom or *sediments*.

The growing crystal, which sediments, has not yet solidified completely but contains melt of interdendritic composition. The melt outside the crystal has another and lower concentration of the alloying element ("bulk liquid"). When the crystal sediments it passes regions with lower alloy composition and the interdendritic melt carried by the crystal is partly rinsed away and replaced by melt from the surroundings. The melt within the crystal obtains an intermediate composition between the concentration of the surrounding melt and the high concentration of the melt in the interdendritic regions inside the crystal.

The exchanged interdendritic melt stays in the upper parts of the ingot and crystals with partly more pure (lower concentration of alloying elements) melt sinks towards the bottom. The result is a *positive* segregation in the *upper* part of the ingot and a *negative* segregation in the *lower* parts.

Simple Mathematical Model of Sedimentation Segregation

Some Definitions

Macrosegregation, due to sedimentation of free crystals, has been treated theoretically. The free crystals contain interdendritic melt and bring additional bulk melt with them when they sediment. In this way one part of crystals is accompanied by W parts of bulk liquid, which get imbedded in the sediment zone. The average concentration of the alloying element in the sediment zone can be calculated from the relation

$$c^+ = \frac{c^s + Wc^L}{1 + W} \quad (75)$$

where

- c^s = concentration of the alloying element in the crystals
 c^L = concentration of the alloying element in the bulk melt
 c^+ = average concentration of the alloying element in the sediment zone.

The partition coefficient is defined as c^s / c^L . The segregation due to sedimentation can be described by an effective partition coefficient k^+ . It can be calculated by dividing equation (75) by c^L .

$$k^+ = \frac{c^+}{c^L} = \frac{k + W}{1 + W} \quad (76)$$

Calculation of the Relative Height of the Sediment Zone

A possible and simplified mechanism for the formation of the equiaxed zone is:

1. Free crystals nucleate, grow in the liquid at a given undercooling and settle simultaneously.
2. No more crystals form in the melt during the settling time.

The concentration of the alloying element in the melt can be calculated by aid of the lever rule (equation (15) on page 15 in chapter 7):

$$c^L = \frac{c^o}{1 - f(1 - k)} \quad (77)$$

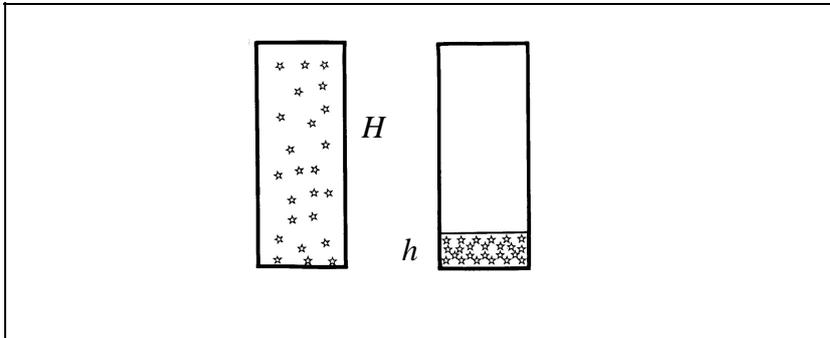
where

- c^o = initial concentration of the alloying element
 f = total volume fraction of solid phase in the melt at the time of sedimentation.

The volume fraction of solid phase can be calculated from equation (77). The result is

$$f = \frac{c^L - c^o}{c^L \cdot (1 - k)} \quad (78)$$

crystals in the
e sedimentation.
crystals,
associated melt, after
ation.



The volume fraction of crystals including their associated melt is a factor $(1 + W)$ times larger than f .

$$f_{\text{crystal}} = f \cdot (1 + W) \tag{79}$$

According to figure 49 the volume fraction of crystals, including their associated melt, can also be written

$$f_{\text{crystal}} = \frac{h}{H} \tag{80}$$

where H and h are the heights before and after sedimentation.

Equations (79) and (80) gives

$$f = \frac{\frac{h}{H}}{1 + W} \tag{81}$$

Example 5.

Find expressions for c^L and c^+ in terms of c^o , k and W .

Solution:

If we replace f in equation (77) by the expression (81) we get

$$c^L = \frac{c^o}{1 - f(1 - k)} = \frac{c^o}{1 - (1 - k) \cdot \frac{h}{H}} = \frac{c^o \cdot (1 + W)}{(1 + W) - (1 - k) \cdot \frac{h}{H}}$$

This expression of c^L in combination with equation (75) gives

$$c^+ = \frac{c^s + Wc^L}{1+W} = \frac{kc^L + Wc^L}{1+W} = \frac{k+W}{1+W} \cdot c^L$$

or

$$c^+ = \frac{k+W}{1+W} \cdot c^L = \frac{k+W}{1+W} \cdot \frac{c^o \cdot (1+W)}{(1+W) - (1-k) \cdot \frac{h}{H}} = \frac{c^o \cdot (k+W)}{(1+W) - (1-k) \cdot \frac{h}{H}}$$

Answer: $c^L = \frac{c^o \cdot (1+W)}{(1+W) - (1-k) \cdot \frac{h}{H}}$ and $c^+ = \frac{c^o \cdot (k+W)}{(1+W) - (1-k) \cdot \frac{h}{H}}$

Calculation of the Sedimentation Segregation

The theory predicts that the average concentration of the alloying element is a simple function of the relative height of the sediment zone. It can be written

$$c^+(h) = c^+(0) \cdot (1 - h/H)^{(k^+-1)} \quad (82)$$

which gives the sedimentation segregation

$$c^+(h) - c^o = c^+(0) \cdot (1 - h/H)^{(k^+-1)} - c^o \quad (83)$$

Equations (83) in combination with equation (76) describes the macrosegregation due to sedimentation of equiaxed crystals if the relative height of the sediment zone, the partition constant and W are known.

A small sediment zone gives a large negative macrosegregation at the bottom of the ingot, but the contribution to the positive macrosegregation at the top will be small.

Influence of Crystal Size on Sedimentation Segregation

Another reason for the fact that the average composition of the sedimented crystals deviates from the initial composition may

be that they, during the sedimentation, have grown at a lower undercooling than the surrounding crystals.

It has been found that in ingots with a fine-grained uniaxed crystal zone the tendency of negative segregation at the bottom is larger than the one in ingots with a uniaxed zone of big crystals. When there is a great number of free crystals in the melt, these grow at a lower undercooling than if there are fewer and bigger crystals. This also facilitates the exchange of melt in the interdendritic regions because the melt flows more easily through broad than narrow channels.

11.9.2 A-Segregations

In section 11.7 we found that the channels in castings, which are called freckles, are caused by natural convection due to temperature and especially concentration gradients in the two-phase region during the solidification process in an ingot.

At the vertical solidification front in an ingot the type of convection appears, which has been mentioned in the preceding section (figure 45 b on page 68). This flow may, in analogy with freckles formation, result in channel formation. These channels are called *A-segregations*. A-segregations are thus caused by natural convection in the melt during the solidification process, due to the density variations and result in macrosegregation in the material.

A-segregations occur in big ingots and appear generally in the upper third part of the ingot up to the upper surface. They are sometimes called "gost lines". A typical example is shown in figure 50.

The circular, nearly vertical channels are formed when melt with a high concentration of the alloying element is carried to a region with a higher temperature than its own and a rest melt with lower alloy composition. The addition of melt from outside leads to a change of the composition in the region, which causes the liquidus temperature to decrease and some crystals to melt. The melt, which flows through the dendritic network, finds its way, where the flow resistance is smallest.

When the melt flows from a colder to a warmer region part of the already formed dendritic network melts and channels are formed according to the same principles, which are valid for freckles formation.

In the same way as described in figure 46 on page 69 we get a positive segregation in the top in this case too. In big ingots the positive segregation in the top is mainly caused by convection in the A-segregation channels. This can be described quantitatively in a relatively simple way.

Simple Mathematical Model of A-segregations

The convection in the A-segregation channels are driven by the density differences in the melt. The convection pattern appears in principle as is seen in figure 51.

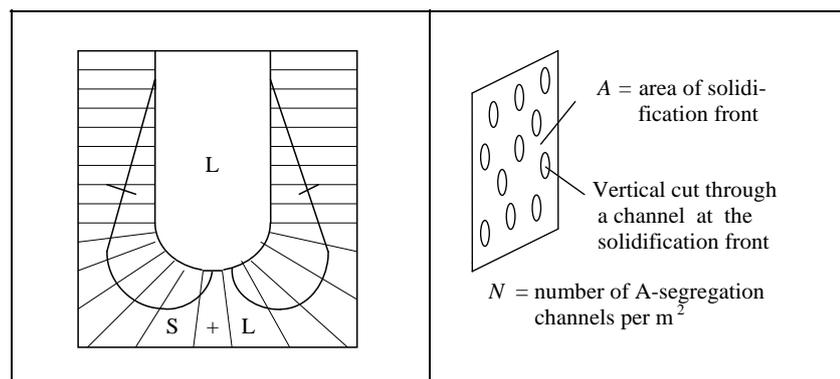


Figure 51. Convection pattern in a solidifying ingot.

Figure 52.

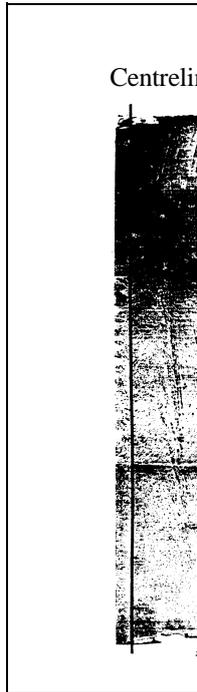


Figure 50. Sulphur print of A-segregations in an ingot.

The bent curves in figure 51 are two streamlines, which illustrate the flow of the melt in the two-phase region. The channel formation starts at the transition from a colder to a warmer region. These positions have been marked in the figure by aid of two cross-strokes.

The directions of the channels coincide with the directions of the flow lines. The channels "intersect" the vertical solidification front under a certain angle and give elliptical intersections with the front surface (figure 52).

The density difference and the number and sizes of the A-segregations determines the segregation pattern, i. e. the size of the macrosegregation.

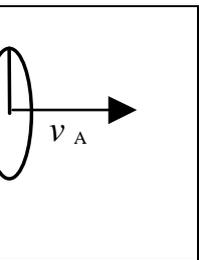
We set up a material balance of the melt, which flows through the A-segregation channels:

$$\frac{dc}{dt} \cdot V = v_A A_A \cdot (c_A - c) \quad (84)$$

Received amount of alloying element per unit time Supplied amount of alloying element per unit time.

where

- c = concentration of alloying element in the melt
- V = volume of the melt
- c_A = concentration of the melt in the A-channels
- v_A = average flux of the melt in the A-channels
- A_A = the total cross-section areas of the A-channels
- t = time.



We have to find expressions for A_A , v_A and V To be able to solve equation (84).

A_A can be connected with the area of the solidification front (see figure 52 by aid of the relation

$$A_A = A \cdot N \cdot \pi r_A^2 \quad (85)$$

where

- A = area of the solidification front
- N = number of A-segregation channels per unit area
- r_A = radius of an A-channel.

The average flux v_A can be calculated by aid of the law of Hagen-Poiseuille, which is valid for a flowing liquid in a tube (equation 20 on page 43 in chapter 3):

$$v_A = \frac{r_A^2 \Delta p}{8\eta l} = \frac{r_A^2 \Delta \rho g l}{8\eta l} = \frac{r_A^2 \Delta \rho g}{8\eta} \quad (86)$$

where

- Δp = pressure difference between the two ends of a tube (channel)
- $\Delta \rho$ = density difference within the two-phase region
- η = viscosity coefficient of the melt
- l = length of the tube (channel).

By combining equations (84), (85) and (86) the concentration change of the molten phase as a function of time can be calculated. The final equation becomes

$$\frac{dc}{dt} = B c \cdot \frac{A}{V} \quad (87)$$

where B is a summarised constant. After integration we get

$$c = c^0 \cdot e^{B \int_0^t \frac{A}{V} dt} \quad (88)$$

where c^0 is the initial concentration of the melt.

It should be observed that both A and V are functions of time and therefore must stay inside the integral sign in equation (88). If we make assumptions about the motion of the solidification front during the solidification it is possible to find expressions for A and V as functions of time during the solidification process, and then perform approximate calculations of the macrosegregation at various heights from the bottom in an ingot.

Figure 54 gives an example of such a calculation of the macrosegregation and a comparison with experimentally measured values. It can be seen from the figure that the macrosegregation is considerable. At the top of the ingot the concentration of the alloying elements is twice as large as in the interior of the ingot. The positive segregation at the top is also influenced, although to a minor extent, by the sedimentation of crystals (page 72) within the ingot.

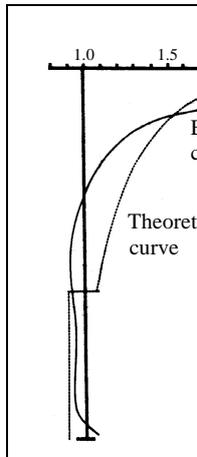


Figure 54. Macrosegregation on central axis in an

11.9.3 V-Segregations

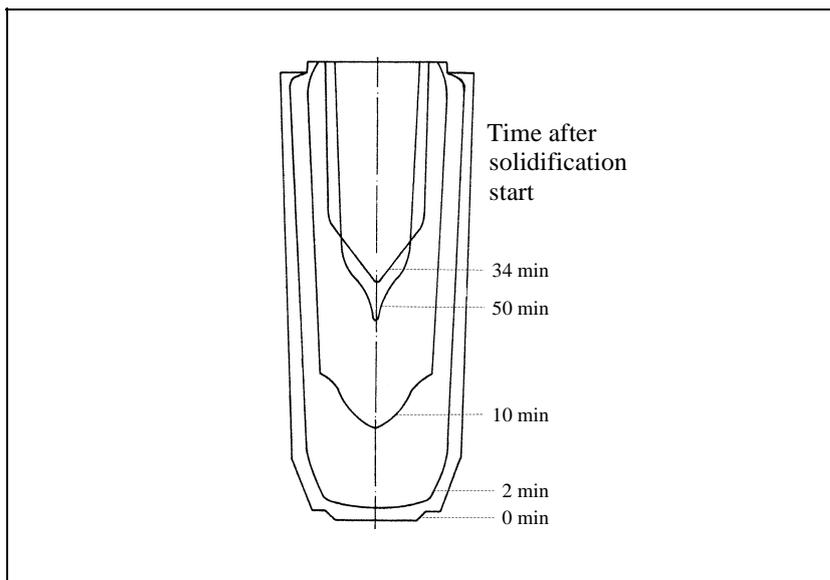
In connection with the treatment of centre segregation at continuous casting of strands we have briefly discussed V-segregations (section 11.6 on page 43). It is apparent from figure 48 on page 71 that they also occur in ingots.

By aid of radioactive tracers the German metallurgist Kohn has studied how the solidification front moved within a 3.5 ton ingot during the solidification process. The result of the experiment is illustrated in figure 55. From the figure it can be seen that

- a layer of solid/liquid material is built up more rapidly from the bottom of the ingot than from the sides
- during the solidification process a strong lowering or dip of material in the centre will occur sometimes within the time interval 34 - 50 min.

A very thick zone with a crystal framework and an interdendritic melt, with strong accumulation of alloying elements, is formed at the bottom.

An explanation of the settling at the centre during the solidification process may be that the freshly formed crystal framework can not stand the ferrostatic pressure but becomes compressed.



e solidification
the solidification
.5 ton ingot as a
me.

Hultgren has given a more likely explanation to the settling. He claims that the vacuum, caused by the solidification shrinkage in the lower parts of the ingot, cannot be filled by melt from above because the distance is long and the resistance from the dendrite arms is great. The pressure difference, which arises for this reason between the different parts of the ingot results in a general settling of the crystals in the middle zone.

This settling causes either a deformation of the crystal framework in the middle zone or framework cracks along regions, which already have achieved a considerable stability. These cracks are filled more or less completely by melt, which has accumulated alloying elements and impurities. Since the pressure, which causes the settling, has a maximum at the centre and decreases radially towards the periphery of the ingot, the cracked parts show a V-shape and have a "stripy" segregation profile.