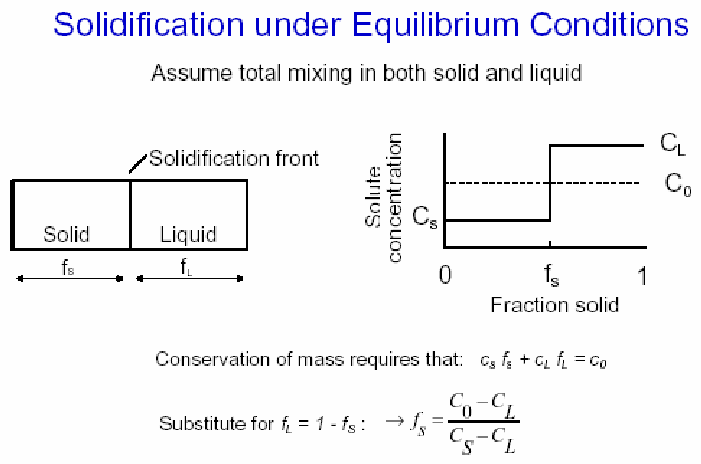
FREEZING OF CASTINGS

Simple Case Analysis

We shall start by considering the movement of a planar solidification front along a bar of liquid metal which contains a solute with an initial concentration of C_o. This type of solidification can be achieved in practice by using a special furnace to impose a steep temperature gradient on a crucible holding the metal. We shall now consider three limiting cases:

a) Equilibrium Solidification

The first of these is equilibrium solidification (**Figure 3204.00.01**). This assumes that total mixing takes place in both the liquid and the solid. This requires complete diffusion to take place in the solid, which is usually impossible! However, it does apply when solutes have a high diffusion rate, examples being hydrogen or carbon in cast irons and steels, or hydrogen in copper. We then allow the liquid metal to start to solidify so that, at a particular temperature, a certain volume fraction of solid has formed, fS, leaving a certain volume fraction of liquid, fL, where $fS + fL = 1$.


Solidification under Equilibrium Conditions

Assume total mixing in both solid and liquid

Conservation of mass requires that: $c_S f_S + c_L f_L = c_0$

Substitute for $f_L = 1 - f_S$: $\rightarrow f_S = \dfrac{C_0 - C_L}{C_S - C_L}$

The law of the conservation of mass requires that:

(Solute in solid) + (Solute in liquid) = (total solute)

and so $$CSfS + CLfL = CO \qquad (1)$$

where *CS* and *CL* are the concentrations of the solute in the solid and liquid respectively. The above equation can be shown to be merely a re-statement of the lever rule by substituting for *fL*. Equation (1) then becomes:

$$CSfS + CL\,(1 - fS\,) = CO$$

Hence

$$f_s \;=\; (\,Co \;-\; Cl)/(Cs \;-\; Cl) \qquad (2)$$

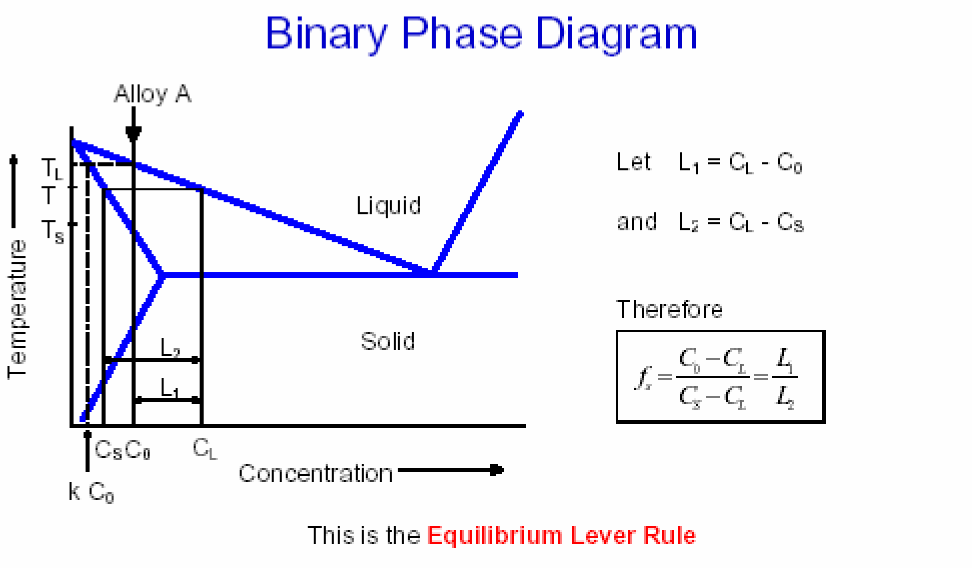


Figure 3204.00.02: Reference to this phase diagram shows the cooling of molten Alloy A having an initial solute concentration of *CO*, a liquidus temperature of *TL* and a solidus temperature of *TS*. At a temperature T where the fraction solid is *fS*, L1 = CL - CO and L2 = CL - CS

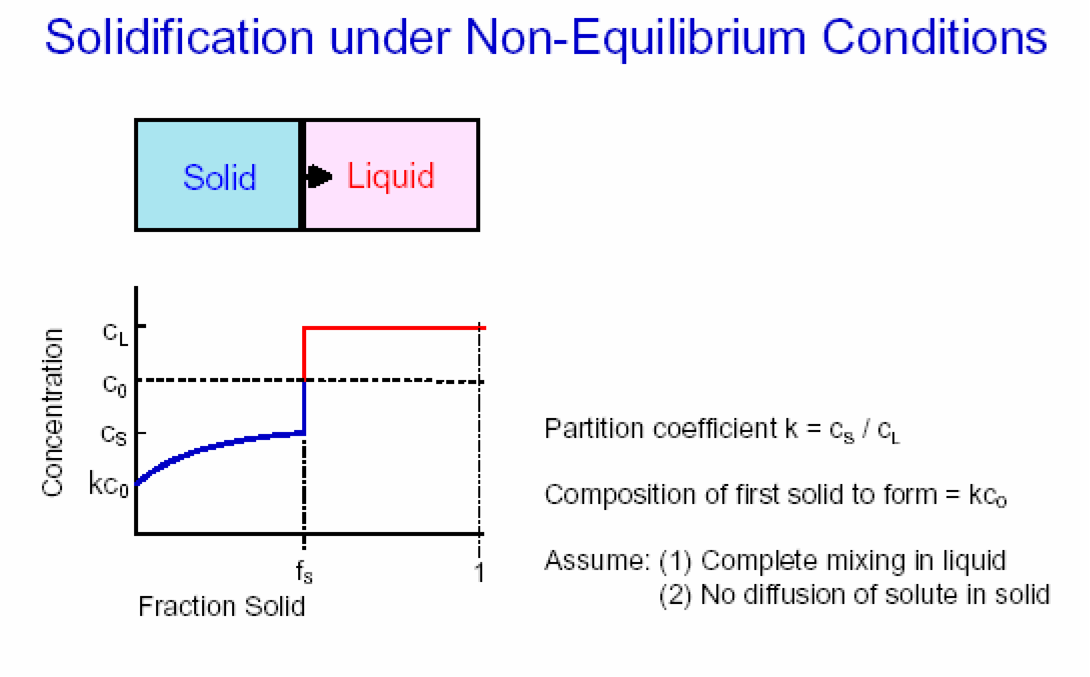
and substitution of these values in equation 2 gives:

$$f_s = L1/L2$$

which is the equilibrium lever rule.

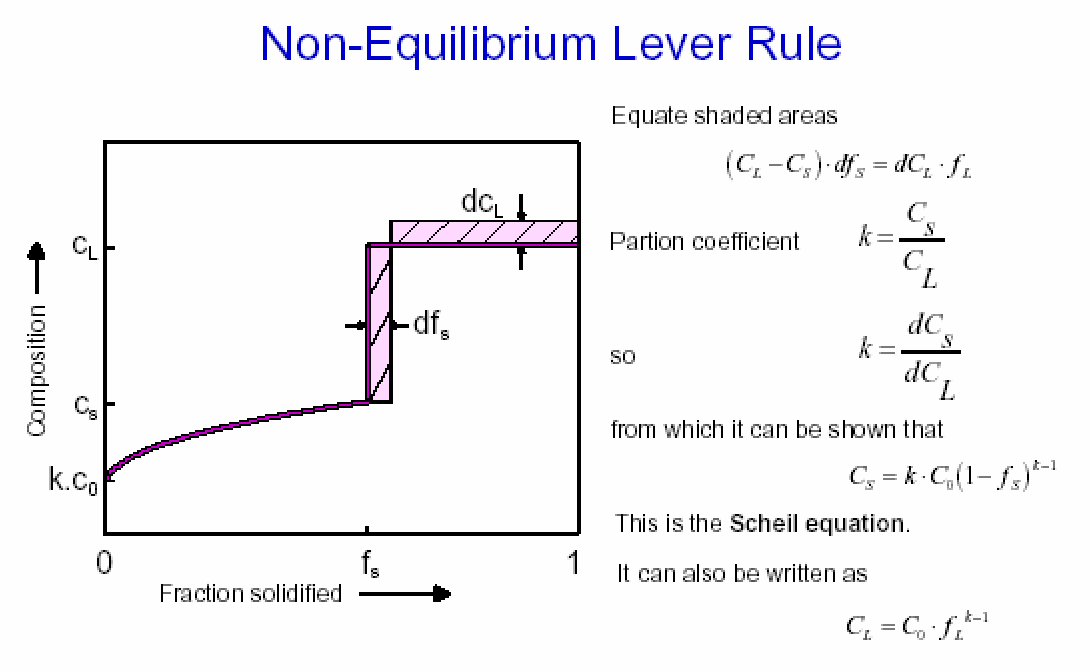
b) Non-equilibrium Analysis

Moving onto the second limiting case, we shall now consider non-equilibrium solidification and derive the Scheil equation which is widely used to describe the solidification behaviour. The top part of **Figure 3204.00.03** again shows the progression of solidification with a front between solid and liquid moving from left to right. The bottom half shows solute concentration as a function of the fraction solid.



The initial uniform solute concentration in the liquid is CO . The first solid to form has a composition of $k \cdot CO$, where k is the partition coefficient and defines how the solute partitions between the solid and liquid phases, i.e. $k = CS / CL$. High values of *k* (close to 1) indicate that the solute is evenly distributed between liquid and solid (i.e. there is little tendency to segregation). As *k* becomes small (for instance, 0.05 for oxygen in iron), so more and more solute is concentrated in the liquid, i.e. segregation increases

(for instance, by a factor of 20 for oxygen in iron). When the initial solid is formed, the excess solute is rejected ahead of the advancing front. The following assumptions are then made: 1. there is efficient mixing in the liquid so that there is a uniform solute distribution, giving a uniform concentration *CL*; 2. there is no diffusion of solute in the solid phase, which can arise if the rate of cooling is high or if the rate of diffusion is low. This is usually quite a good approximation for most substitutional solutes, such as Mn in Fe, or Cu in Al.



Non-Equilibrium Lever Rule

Equate shaded areas

$$(C_L - C_S)\cdot df_S = dC_L \cdot f_L$$

Partion coefficient $k = \frac{C_S}{C_L}$

so $k = \frac{dC_S}{dC_L}$

from which it can be shown that

$$C_S = k \cdot C_0 (1 - f_S)^{k-1}$$

This is the **Scheil equation**.

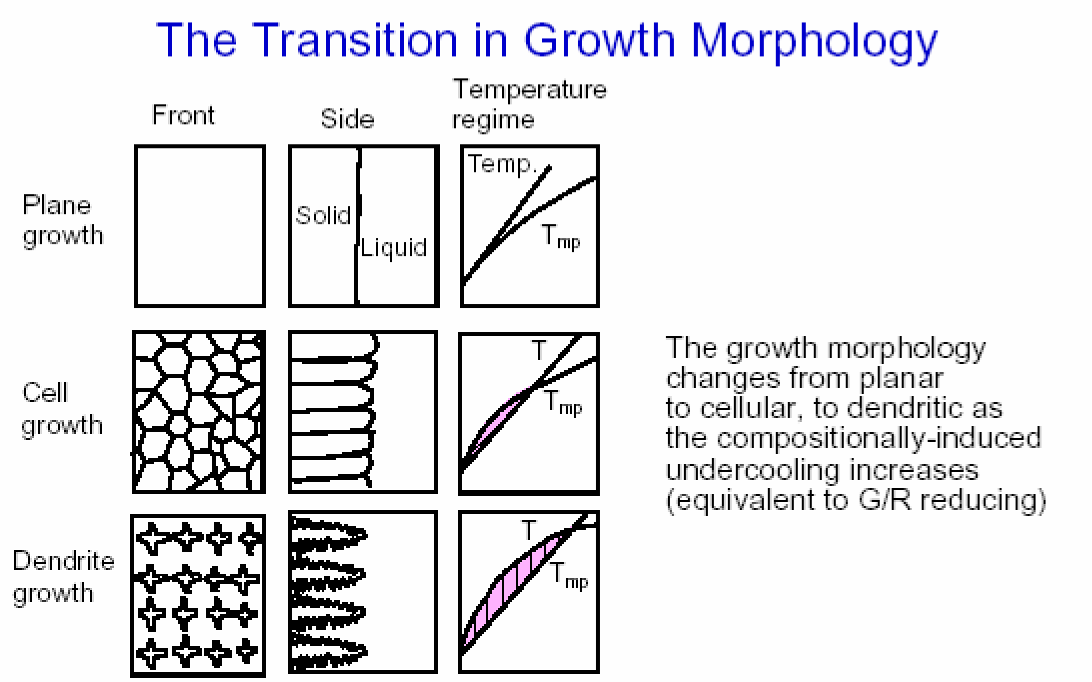
It can also be written as

$$C_L = C_0 \cdot f_L^{\,k-1}$$

More details frm pdf

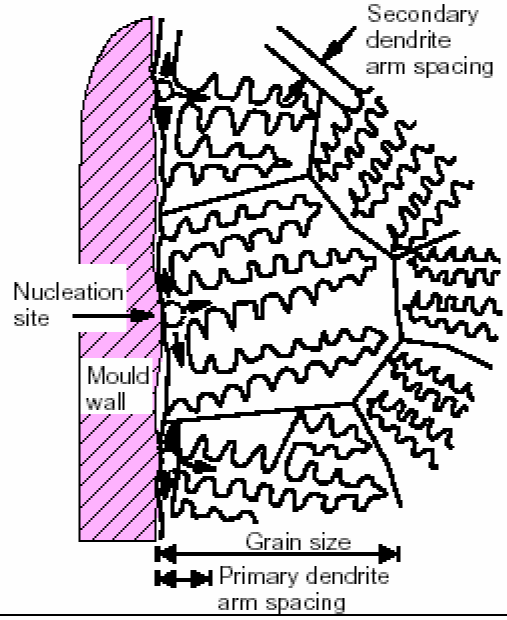
Transition in Growth Morphology

Figure 3204.00.10 shows how the growth morphology changes from planar to cellular and then to dendritic as the compositionally-induced 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 constitutional undercooling condition is high.



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, with the secondary arms generating more primaries (see **Figure 3204.00.11**). 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.

The Formation of a Raft of Dendrites to Make Grains



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 secondary dendrite arm spacing, often abbreviated to 'dendrite arm spacing', or DAS. This average length is usually measured by carrying out a line count along the length of a number of primary dendrite stems which happen to lie near to the plane of the section. During the growth of the dendrite, the average dendrite arm spacing 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 (**Figure 3204.00.12**). 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, *d*, is largely a function of the solidification time, *tS*, and the relationship is of the approximate form:

$$d = k \cdot tS^{\,0.3}$$

The overhead shows a typical set of results for an Al-4.5%Cu alloy in which the dendrite arm spacing is plotted as a function of the solidification time (note that a log scale has been used). The above relationship can be seen to hold over an impressive 8 orders of magnitude.

Grain size is usually measured by a linear intercept method in which a fixed distance is divided by the number of grains crossed. Grains can be considerably larger than the DAS but, of course, the reverse is not possible. This is also illustrated by these results.

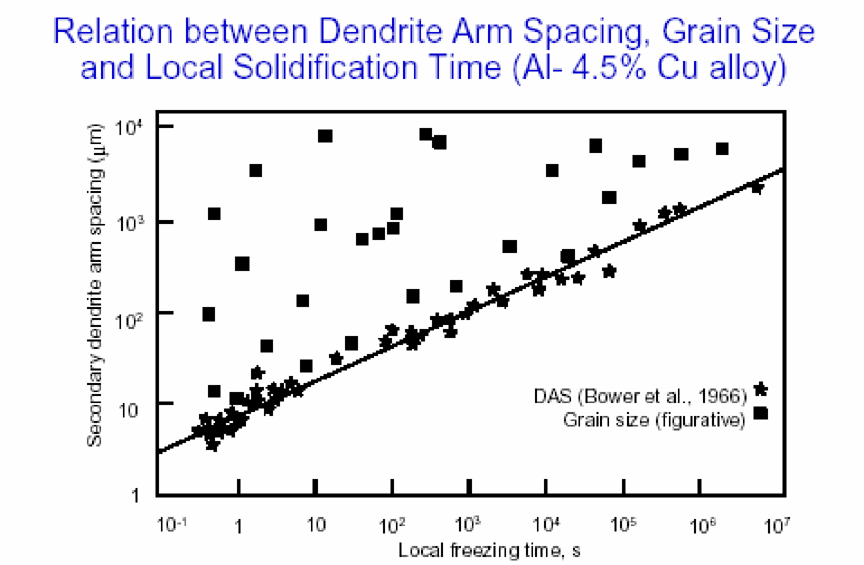


Figure 3204.00.13: The mechanical properties of most cast alloys depend strongly on DAS: the tensile strength, ductility and elongation all increase as DAS decreases. A small DAS also reduces the time required for homogenisation heat treatments since the diffusion distances are shorter. It is therefore beneficial to reduce the

DAS as far as possible and since this is almost exclusively a function of the freezing time, any technique to reduce this will have a beneficial effect upon the DAS. In the case of sand casting, metal chills will help considerably in reducing the DAS. Die castings will have a finer DAS, and lower die temperatures will assist even further.

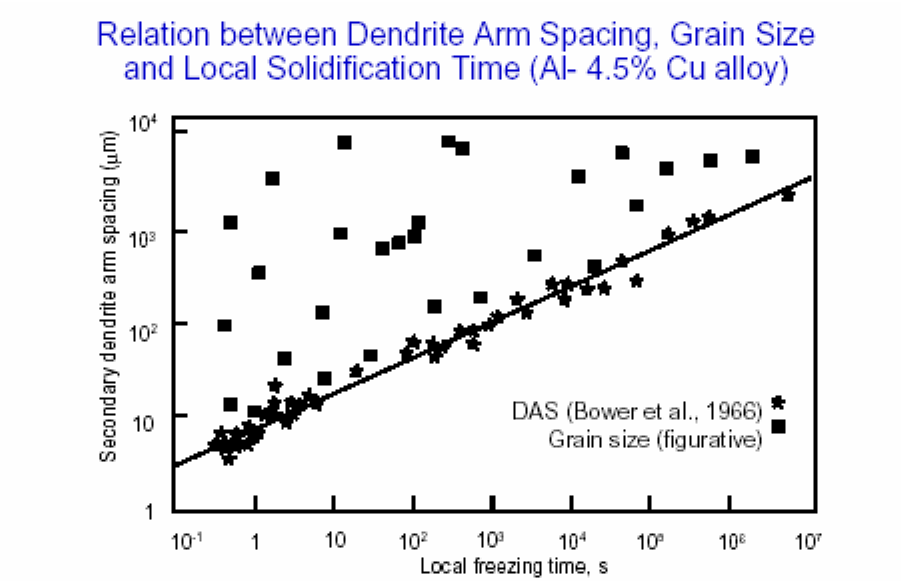
Why is Dendrite Arm Spacing Important?

As dendrite arm spacing increases:

- Tensile strength increases
- Ductility and elongation increase
- Hardness increases
- Shorter homogenization heat treatment required

Grain Refinement

I would now like to consider grain refinement by reference to the graph (**Figure 3204.00.14**) that we have just seen. Although grain size does tend to reduce somewhat as freezing time is decreased, it is not closely controlled by the freezing time. This is clearly illustrated by the general scatter in grain sizes above the $d = k \cdot (tS)^{0.3}$ line on this graph. Clearly, a number of other factors control the grain size.



Relation between Dendrite Arm Spacing, Grain Size and Local Solidification Time (Al- 4.5% Cu alloy)

Figure 3204.00.15: The first of these may be homogeneous nucleation. It can be hypothesised that microscopic regions adjacent to the mould wall may be supercooled by several hundreds of degrees K and thereby promote homogeneous nucleation. This is because an oxide skin is normally against the mould wall and the inside surface of this is not an effective nucleus for the initiation of solid. Hence, large amounts of super cooling may take place before nucleation occurs.

Grain Refinement:

- Homogenous nucleation
- Heterogeneous nucleation
- Fragmentation / multiplication
    - Low pouring temperature
    - Mechanical, thermal or solutal disturbance
- Restrict grain growth

EFFECT OF ALLOY ELEMENTS

Effect of silicon in Aluminum alloys:

1. Fluidity increases
2. Solidification shrinkage decreases
3. Pressure tightness improves
4. Modulous of elasticity increases
5. Specific gravity increases
6. Thermal expansion increases
7. Corrosion resistance increases

Normal silicon content in Aluminum alloy is 11.7%. As silicon content is increased above 11.7% to approximately 17%, fluidity and wear resistance increase significantly due to presence of primary silicon in the alloy. Silicon contributes to fluidity largely due to its high heat of crystallization. When silicon solidifies, it releases a large amount of heat, reheating the remaining liquid aluminum, delaying the solidification and allowing the mass to continue flowing.

Effect of Copper in Aluminum alloys:

Copper content is controlled to improve desirable characteristics and restricted to reduce others, particularly atmospheric corrosion. Copper content in the range of 2.0% - 3.0% increase the tensile strength and hardness and improves mechanical properties at elevated temperatures. In these concentrations it marginally influences alloy density. Copper is more than three times as dense as aluminum. The principal disadvantage of copper in Al-Si-Cu alloy, as noted above is the marked effect of corrosion resistance. Corrosion resistance decreases with copper content.

Effect of Magnesium in Aluminum alloys:

Higher concentrations particularly above 0.3% tends to reduce ductility, and in extreme cases embrittlement may occur. Precise control of Magnesium content within a specified range can enhance chip formation and removal in machining operations. Magnesium in a controlled addition, contributes to strength and hardness, which are otherwise lost by restricted copper content.

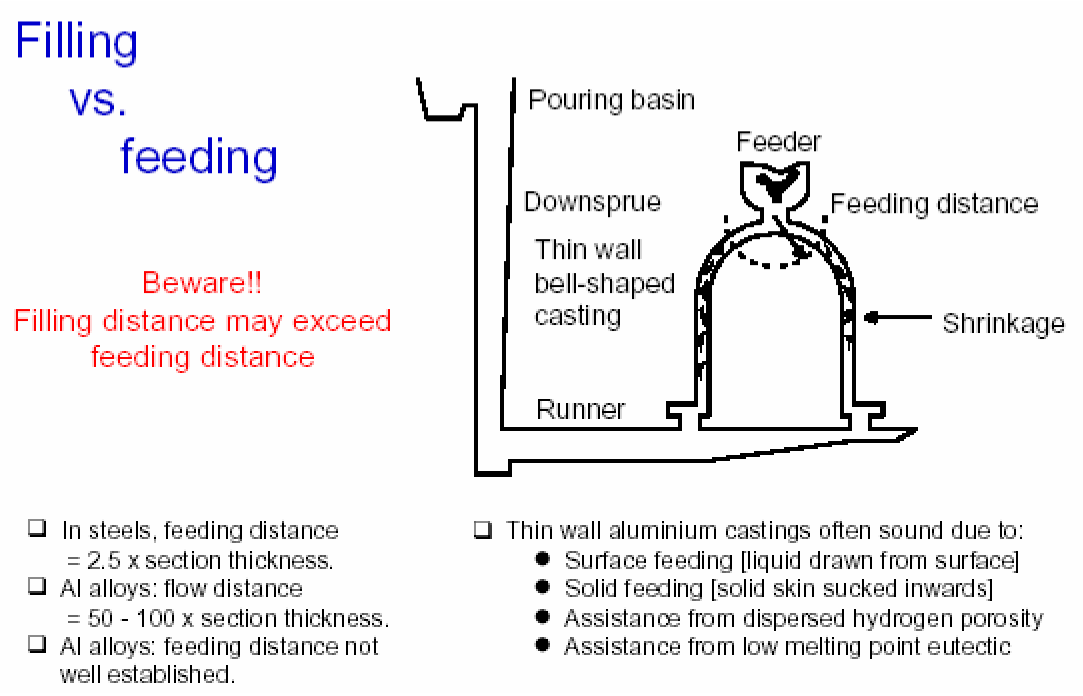
Effect of Iron in Aluminum alloys:

Iron is necessary in aluminum die casting alloys because Iron free liquid aluminum alloy aggressively attacks ferrous metals, including die steels causing severe die erosion. It also tends to stick, or solder onto die surfaces. Iron in Al alloys in the range of 0.6% - 1.2% tends to prevent these conditions and helps to inhibit hot – shortness. Iron is essentially insoluble in solid aluminum. In aluminum alloy microstructure, iron occurs as an intermetallic compound that forms as needles or plates. The particles affect ductility adversely and often act as fracture initiation sites.

PRACTICAL FEEDING PROBLEMS

Figure 3205.00.17: Finally, a significant practical difficulty needs to be emphasised for the benefit of the unwary casting technologist. It needs to be pointed out that although an alloy may be persuaded to flow a considerable distance to fill a mould, this flow distance may greatly exceed the distance to which the alloy may be fed. Thus although the mould may have been successfully filled, so that the casting may appear to be reassuringly complete when taken out from the mould, the casting may be scrap in any case as a result of internal shrinkage problems, simply because the metal has been allowed to flow to a greater distance than can easily be fed. Unfortunately, it is not easy at this time to give any easy guidance on this important issue. The reason is that despite a number of attempts to clarify this issue by research on the feeding distance of aluminium casting alloys, the results have been unclear. This is perhaps not surprising because the physical laws controlling feeding distance are complicated (we shall briefly take a look at these in a moment). The imprecise situation for aluminium alloys contrasts with the precise and well known condition in simple carbon-manganese steels of section thickness upwards of 15 mm cast in green sand moulds. Here the feeding distance is easily demonstrated to be a maximum of 2.5 times the section thickness away from the feeder.

However, as a useful rule of thumb, most common aluminium foundry alloys in a sand mould will flow a distance of at least 50 times the section thickness in a complex casting, and up to 100 times the section thickness in a simple, nicely gated casting. (Beyond this are usually the headaches of regular scrap due to misrun castings. Beware!) It is likely therefore that the feeding distance might be considerably exceeded in aluminium alloys, and some castings are indeed observed to contain some centre-line shrinkage porosity beyond a distance of a few section thicknesses from the feeder.



Filling
vs.
feeding

Beware!!
Filling distance may exceed feeding distance

- ☐ In steels, feeding distance = 2.5 x section thickness.
- ☐ Al alloys: flow distance = 50 - 100 x section thickness.
- ☐ Al alloys: feeding distance not well established.

- ☐ Thin wall aluminium castings often sound due to:
  - ● Surface feeding [liquid drawn from surface]
  - ● Solid feeding [solid skin sucked inwards]
  - ● Assistance from dispersed hydrogen porosity
  - ● Assistance from low melting point eutectic

However, this is not always the case. Many thin sections which have been run to the maximum fluidity distance are still found to be sound when checked by X-ray radiography. This appears to be the result of the beneficial actions of other feeding processes such as:

surface feeding, in which liquid to feed internal shrinkage is withdrawn from the nearby casting surface. (In a thin section casting this feeding mechanism has a negligible effect on surface finish),

solid feeding, in which the solid skin of the casting is sucked inwards. Once again, this is a negligible effect on casting dimensions when well-dispersed over an extensive thin wall.

Other effects which are occasionally present and which have an important influence on whether the casting freezes sound or not are:

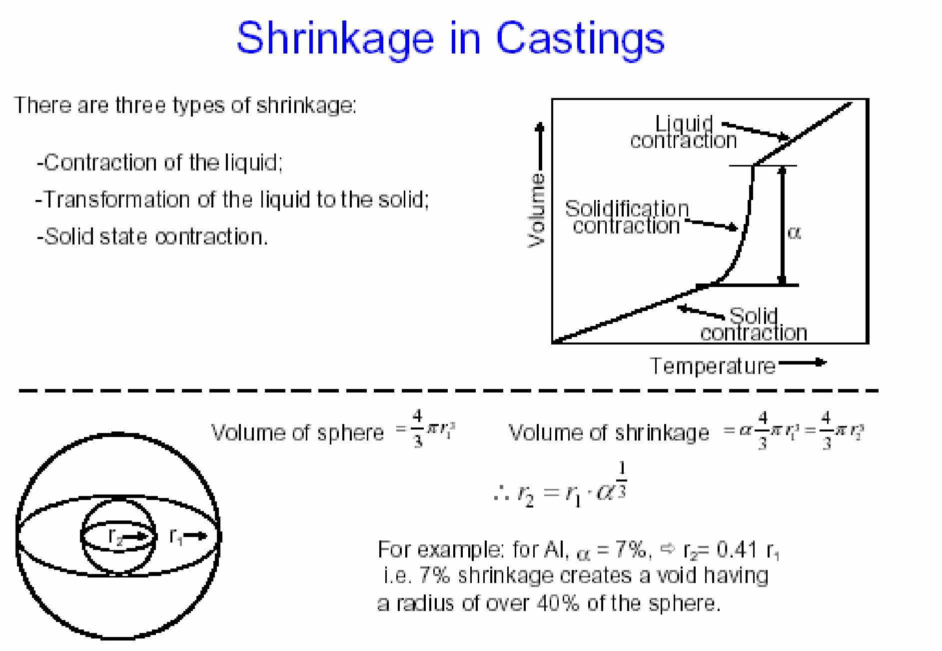
The occasional presence of some dispersed hydrogen porosity which will reduce the feeding difficulties.

Some alloys seem to enjoy the additional beneficial effects of minute traces of impurities in creating a low melting point eutectic phase which aids feeding. For extensive thin-walled aerospace castings the fluidity and the soundness of the casting are of paramount importnace. However, in the manufacture of many thin walled aluminium alloys castings or normal large commercial markets, the soundness requirements are in most cases easily met because the castings often require no great mechanical properties, but are merely required to be leak-tight. No X-ray requirements are therefore imposed, and a certain amount of internal porosity (whether shrinkage or gas) as a result of exceeding the feeding distance, is of little consequence to the serviceability of the component. Clearly, the ultimate criterion has to be fitness for purpose at minimum cost.

FEEDING OF CASTINGS

Shrinkage Problems

The primary objective of this lecture is to consider how to produce castings that are free from defects caused by shrinkage of the metal. It is important to appreciate that there are three types of shrinkage. Firstly, any liquid metal will contract in volume as it cools from its initial temperature down to its freezing point. This contraction is linear with temperature and can be compensated for without much difficulty. Secondly, there is always a volume change as the liquid metal transforms to a solid due to the change in the arrangement of the atoms from the rather open, random close-packed manner in a liquid to a regular close-packed form in a solid. Examples of the latter are face-centered cubic (f.c.c.) and body-centered cubic (b.c.c.). Finally, there is the contraction of the solid metal as it cools down to room temperature (see **Figure 3206.00.01**).



Shrinkage in Castings

There are three types of shrinkage:

- Contraction of the liquid;
- Transformation of the liquid to the solid;
- Solid state contraction.

Volume of sphere $= \frac{4}{3}\pi r_1^3$

Volume of shrinkage $= \alpha \frac{4}{3}\pi r_1^3 = \frac{4}{3}\pi r_2^3$

$$\therefore r_2 = r_1 \cdot \alpha^{\frac{1}{3}}$$

For example: for Al, $\alpha = 7\%$, ⇨ $r_2 = 0.41\ r_1$
i.e. 7% shrinkage creates a void having
a radius of over 40% of the sphere.

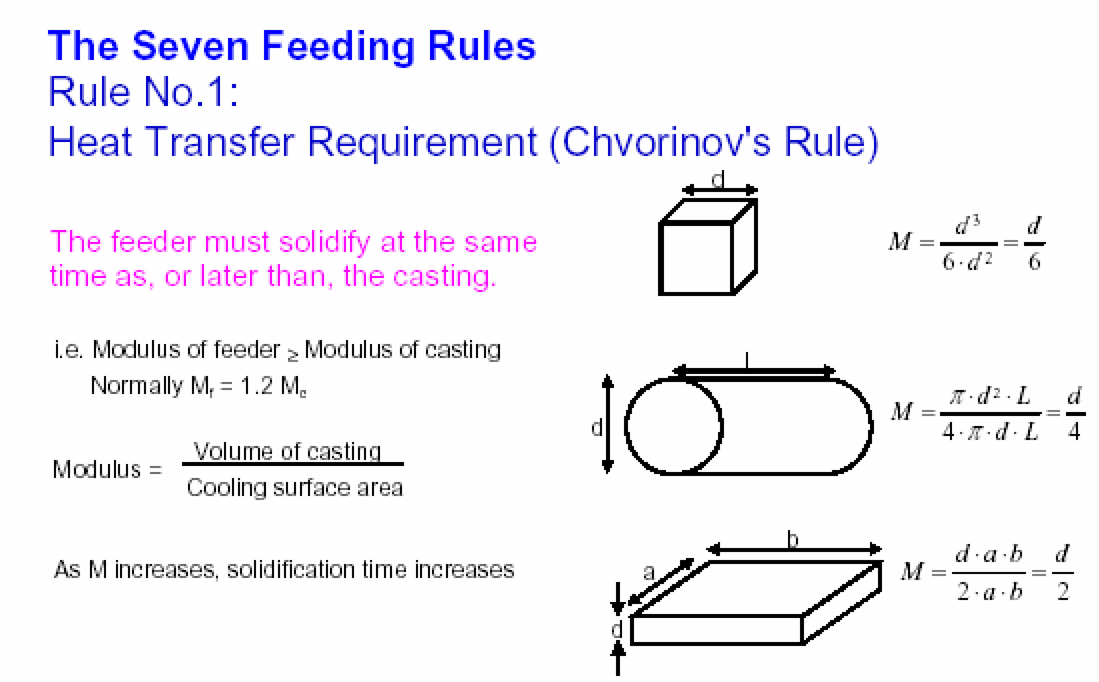
Of these, the transformation from liquid to solid is the most critical. Normally this is a contraction i.e. the metal undergoes shrinkage as it solidifies. Typical values of a are 7% for aluminium and 3.2% for iron. (However, it should be noted that some metals expand on freezing, examples being bismuth and silicon.) Although 7%

shrinkage may not sound very much, it is instructive to consider a simple mathematical treatment of the solidification of a sphere. This shows that it creates a void in the centre of a sphere having a diameter which is 41% of the original sphere diameter. This void must be filled up if the casting is to be sound, but this often causes a real problem in practice. This lecture considers how such shrinkage defects are prevented by the use of a reservoir of molten metal, normally called a feeder in English, but often referred to as a riser in American English.

The Seven Feeding Rules

1) Heat Transfer Requirement

Although much has been written about the feeding of castings, it can be summarised in the form of a set of relatively simple rules, which we shall now consider in detail.



The Seven Feeding Rules

Rule No.1:

Heat Transfer Requirement (Chvorinov's Rule)

The feeder must solidify at the same time as, or later than, the casting.

i.e. Modulus of feeder $\geq$ Modulus of casting

Normally $M_f = 1.2\ M_c$

$$\text{Modulus} = \frac{\text{Volume of casting}}{\text{Cooling surface area}}$$

As M increases, solidification time increases

$$M = \frac{d^3}{6 \cdot d^2} = \frac{d}{6}$$

$$M = \frac{\pi \cdot d^2 \cdot L}{4 \cdot \pi \cdot d \cdot L} = \frac{d}{4}$$

$$M = \frac{d \cdot a \cdot b}{2 \cdot a \cdot b} = \frac{d}{2}$$

The first rule (see **Figure 3206.00.02**) is a heat transfer requirement known as Chvorinov's Rule. It can be stated as:

"the freezing time of the feeder must be at least as long as the freezing time of the casting".

It can be re-stated in simple terms as:

"the modulus of the feeder must be equal to or greater than the modulus of the casting".

More often, it is written as:

"the modulus of the feeder (Mf) equals 1.2 times the modulus of the casting (Mc)".

The extra 20% given by this expression is a safety factor to allow for errors and difficulties in calculating the moduli. The modulus is, of course, defined as the solidifying volume divided by the surface area of the casting which is losing heat. It is important to include *only* those surfaces which lose heat. As the modulus increases, so the solidification time ts increases, and the modulus is therefore a useful means of predicting solidification times.

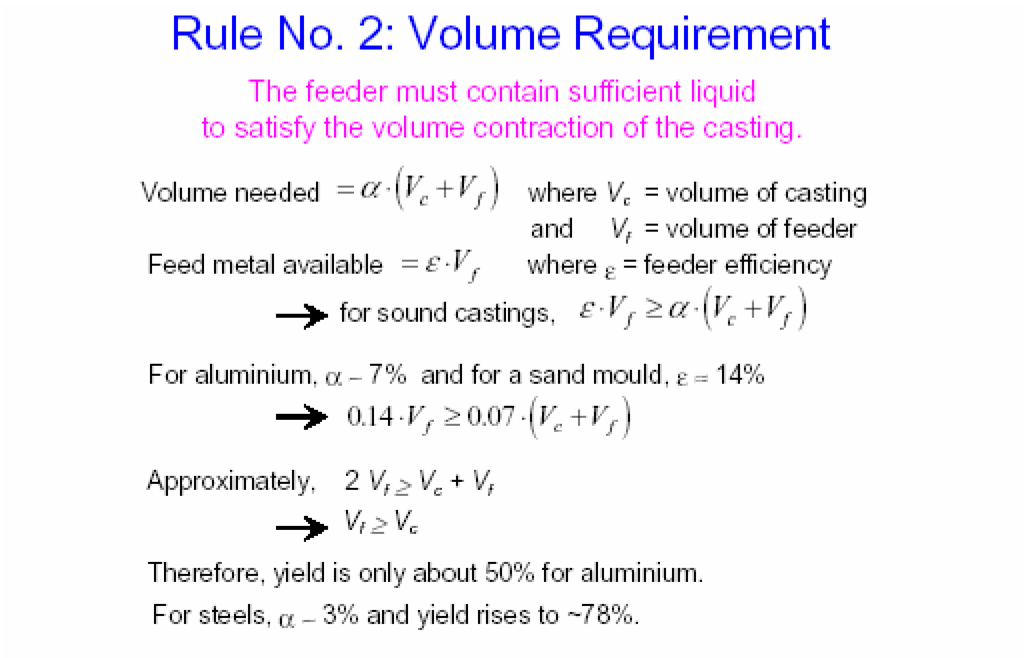
Some modulus calculations for simple shapes are shown here:

– The modulus of a cube having a side of d is d/6.

– For a very long cylinder of diameter d and length L, the volume is π·d2·L/4 and the cooling surface area is π·d·L which gives a modulus of d/4. In this case it has been assumed that no heat is lost from the two end surfaces which is a good approximation if L is much greater than d.

– The volume of a thin plate is d·a·b and the cooling surface area is 2·a·b to give a modulus of d/2. In this case, it has been assumed that the thickness, d, is much smaller than a or b, so that the amount of heat lost through the side faces is negligible. When a and b are not negligible, then the heat lost through the side faces is easily taken into account. When working out the modulus of a complex casting, it is normal to consider those parts that are in good thermal communication as a whole. Thus an aluminium casting can often be treated as a whole because of its high thermal conductivity. C conversely, a steel casting is often dealt with as a series of separate primitive shapes. It should be noted that the modulus always has the dimensions of length.

2) Volume Requirement



Rule No. 2: Volume Requirement

The feeder must contain sufficient liquid
to satisfy the volume contraction of the casting.

Volume needed $= \alpha \cdot \left(V_c + V_f\right)$ where V_c = volume of casting
and V_f = volume of feeder

Feed metal available $= \varepsilon \cdot V_f$ where ε = feeder efficiency

→ for sound castings, $\varepsilon \cdot V_f \geq \alpha \cdot \left(V_c + V_f\right)$

For aluminium, α – 7% and for a sand mould, ε = 14%

→ $0.14 \cdot V_f \geq 0.07 \cdot \left(V_c + V_f\right)$

Approximately, $2\ V_f \geq V_c + V_f$

→ $V_f \geq V_c$

Therefore, yield is only about 50% for aluminium.

For steels, α – 3% and yield rises to ~78%.

The second feeding rule is normally known as the Volume Requirement (**Figure 3206.00.03**). It can be stated as:

"The feeder must contain sufficient liquid to satisfy the volume contraction

requirements of the casting".

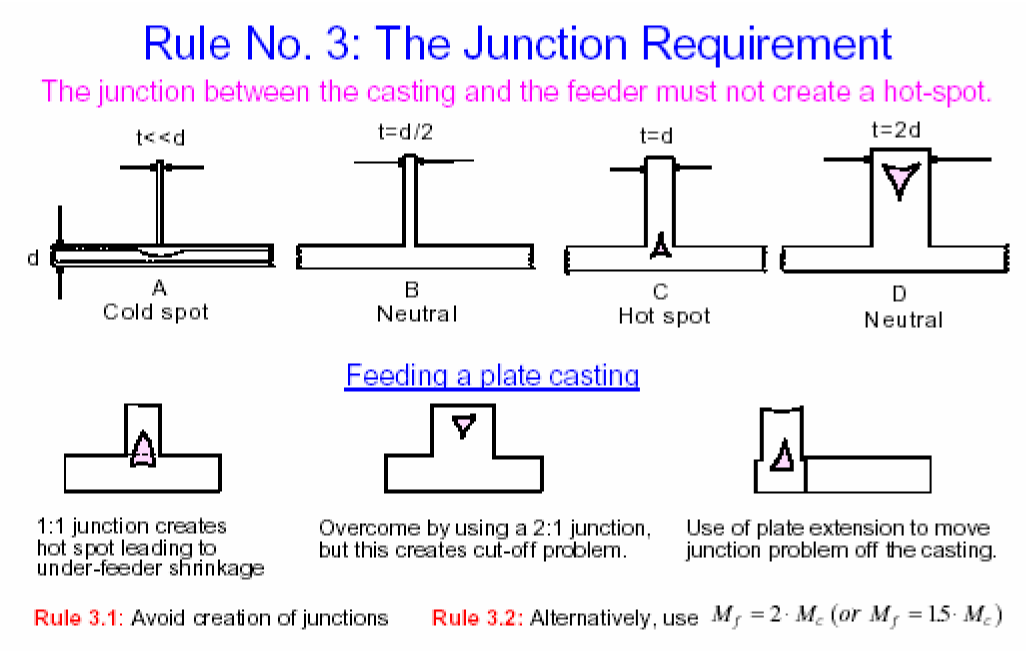
Even if Rule 1 has been closely followed to give $Mf >> Mc$, it is still possible that there may not be enough liquid metal to feed the casting, with the result that the feeder would be emptied and a shrinkage cavity would extend into the casting. An example of when this could occur would be a long thin casting. The volume required can be calculated from the volumetric contraction, α, and the volumes of the casting (Vc) and feeder (Vf), so that Volume required = $\alpha (Vc + Vf)$

This has to supplied by the feeder, which only works with a certain efficiency, ε, so that sound castings will be produced if:

$$\varepsilon . Vf = \langle (Vc + Vf)$$

As an example, α for aluminium is about 7% and ε for a typical feeder moulded in a sand mould is 14%. Substituting these values into this expression shows that, as an absolute minimum, the volume of the feeder must equal that of the casting. It can therefore be seen that aluminium has a very high feed metal requirement since the yield (i.e. weight of casting as a proportion of the weight of the casting plus feeder) is only 50%. For steels with a typical α value of 3%, a feeder of the same efficiency would provide a yield of over 78%. It should also be pointed out that it is possible to improve the yield by insulating the feeder which can increase ε to 50% or higher. Before moving onto Rule 3, it can be commented that many text books only consider Rules 1 and 2, yet there are additional rules which must be followed if sound castings are to be made.

3) Junction Requirement



Rule No. 3: The Junction Requirement

The junction between the casting and the feeder must not create a hot-spot.

Feeding a plate casting

1:1 junction creates hot spot leading to under-feeder shrinkage

Overcome by using a 2:1 junction, but this creates cut-off problem.

Use of plate extension to move junction problem off the casting.

Rule 3.1: Avoid creation of junctions

Rule 3.2: Alternatively, use $M_f = 2 \cdot M_c$ $(or\ M_f = 1.5 \cdot M_c)$

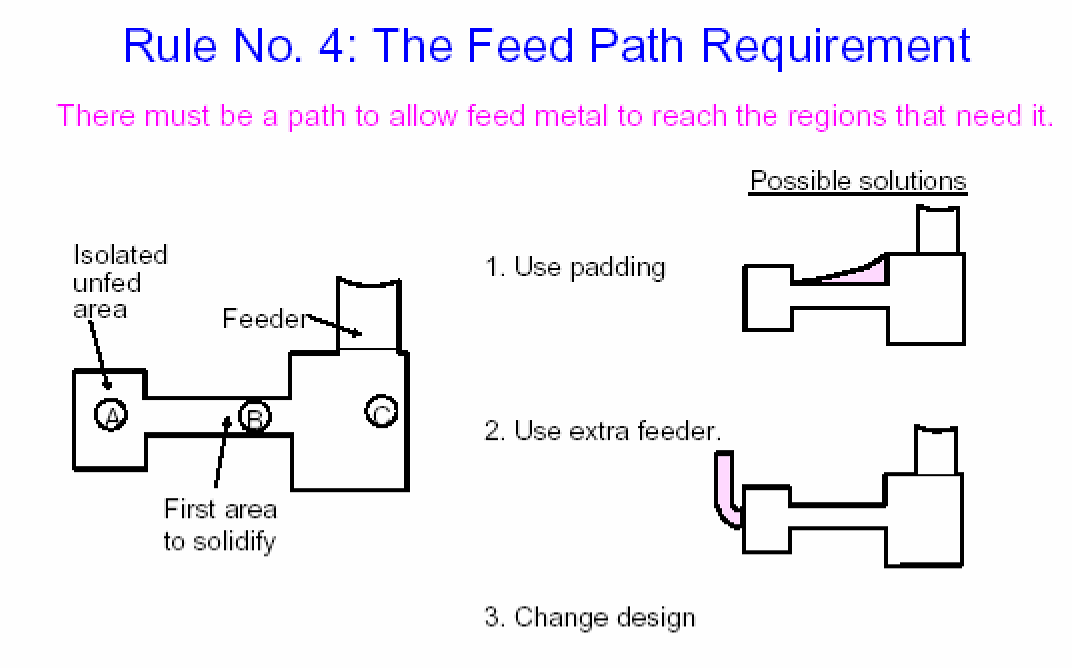
The next rule is known as the Junction Requirement (**Figure 3206.00.04**). This states that the junction between the casting and the feeder must not create a hot spot. This shows a series of T-junctions between a plate of thickness *d* and an adjoining plate of varying thickness *t*. Junction A consists of a thin fin of thickness $t << d$ joined to the plate. It does not take too much imagination to see that the fin will act as it would on a radiator: it will extract heat rapidly, leading to a change in the thermal profiles and the solidification front. In effect, Junction A acts as a cold junction. This effect is sometimes exploited when it is necessary to achieve more rapid cooling locally, as an alternative to chills placed in the mould. It is especially useful when wishing to provide local cooling in aluminium alloys because of their high thermal conductivity. Such junctions are much less effective in steel castings. If we now jump to junction C where we have two legs of equal thickness ($d = t$) joined together. This creates a hot spot, a fact which is well known to all foundrymen! Solidification proceeds less rapidly at the junction of the T because the sand gets very hot in this area. As a result, the fragile solidified skin collapses in this area, leading to a 'wormhole' into the casting. This type of junction must always be avoided. Moving to junction B, logic allows us to guess that when one plate of thickness d is joined to a plate of half of that thickness, the cold and hot junction effects are balanced to give a neutral junction. This means that junction B can be used as an ingate since it has no effect on the casting. Moving to junction D, this can be seen to have a 2:1 ratio and its geometry is herefore similar to that of junction B. This means that it is also neutral and this arrangement is useful as a feeder. We shall now emphasise the importance of the Junction Requirement by considering how to place a feeder on a plate casting. As we have already seen, Chvorinov's rule would suggest that satisfactory feeding should occur if *Mc* is equal to *Mf*. However, if we place the feeder on the casting as shown here, we will create a hot spot because we have overlooked the Junction Requirement. As a result, we will inevitably get shrinkage porosity at the base of the feeder, which is also known as under-riser porosity. From the previous discussion on junction design we can see that this problem can be vercome by enlarging the junction between the plate and the feeder. However, this leads to a large feeder which is difficult to cut off the casting.

This difficulty can be overcome by trying to avoid junctions altogether and one way to achieve this rather contradictory aim is to extend the casting and to put the feeder on that. Rule 3 can therefore be written in two parts. Rule 3.1 is to avoid the creation of junctions, particularly T junctions. However, if there is no alternative to placing a feeder directly on a casting, then Rule 3.2 is to ensure that the modulus of the feeder is twice that of the casting to prevent a hot spot in the casting. This is a theoretical value and in reality it should be possible to reduce this to perhaps $Mf \sim 1.5\ Mc$ (the research to provide an exact factor has not yet been carried out), but it is important *not* to use

Mf ~ 1.2 Mc, which is too close to *Mf ~ Mc*.

4) Feed Path Requirement

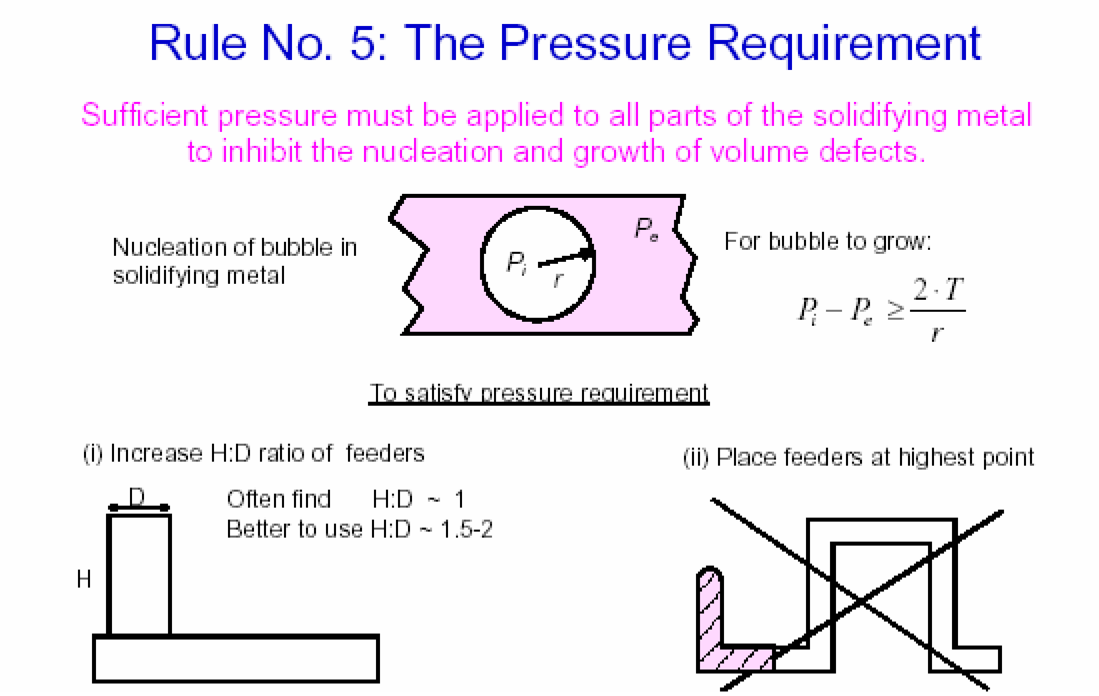
Rule number 4 is known as the Feed Path Requirement (**Figure 3206.00.05**). This states that it is necessary to have communication between the feeder and the feature on the casting which is being fed. This might appear to be rather obvious and trivial, but it is often overlooked and is often difficult to achieve.



This shows a section through a typical flanged wheel casting and we shall assume that the modulus calculations indicate that it should be possible to feed this with a single feeder placed on one of the heavy sections (C). It can easily be seen, however, that the feed path to the other heavy section (A) will be cut when the thinner section B solidifies. One way of overcoming this, which is widely used in steel foundries, is to use 'padding', i.e. to add extra material so that the feed path is kept open. The extra material then has to be removed, which adds to the manufacturing cost. One alternative is to use an extra feeder, although this is not always feasible and may be difficult to remove. A further possibility is to apply a chill or cooling fin to A (not shown on the overhead). A better alternative may be to negotiate a change of design with the customer, although again this may not always be possible.

5) Pressure Requirement

Rule number 5 (**Figure 3206.00.06**) is known as the Pressure Requirement but it is not so obvious as the others. It should firstly be appreciated that most defects - such as porosity or hot tears -are volume defects, that is, they are induced by the volume changes which occur as a casting solidifies. It follows that if a pressure is applied to a solidifying liquid, it is difficult for the defects to nucleate. Rule 5 is therefore that sufficient pressure must be supplied to all parts of the solidifying metal to inhibit the nucleation and growth of volume defects.



Rule No. 5: The Pressure Requirement

Sufficient pressure must be applied to all parts of the solidifying metal to inhibit the nucleation and growth of volume defects.

Nucleation of bubble in solidifying metal

For bubble to grow:

$$P_i - P_e \geq \frac{2 \cdot T}{r}$$

To satisfy pressure requirement

(i) Increase H:D ratio of feeders

Often find H:D ~ 1
Better to use H:D ~ 1.5-2

(ii) Place feeders at highest point

This shows an embryo bubble of radius r having an internal pressure Pi which is trying to grow in an environment which imposes an external pressure Pe. In order for the bubble to grow, it is necessary for the pressure difference to be greater than the restraining force offered by the surface tension, i.e. to satisfy the requirement that:

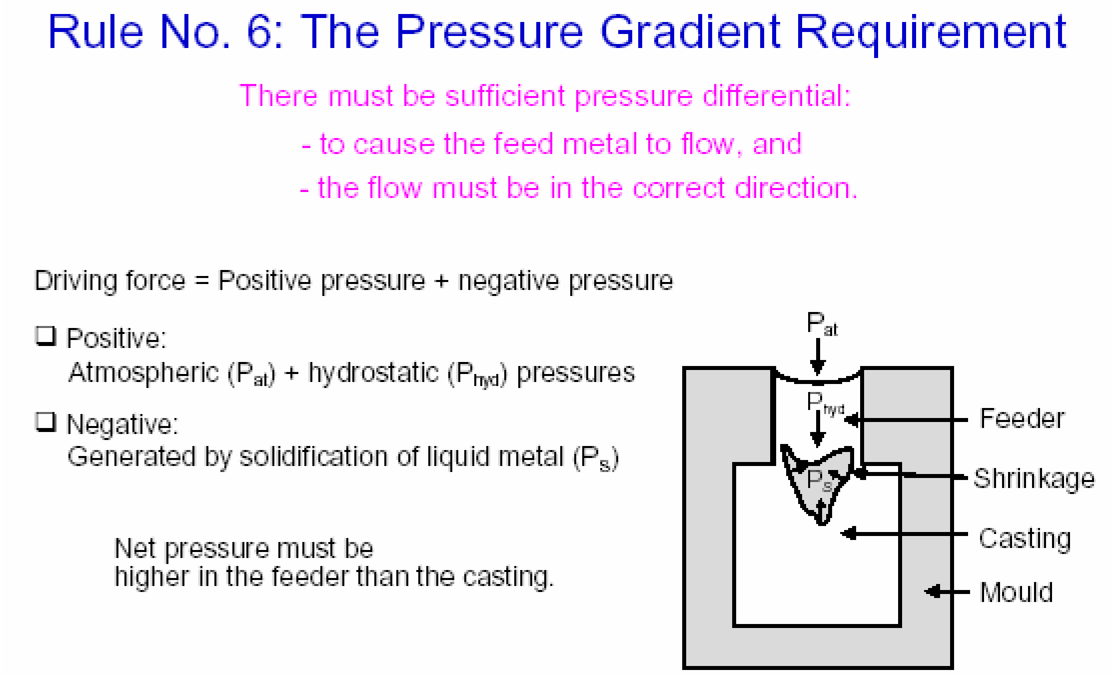
Pi – Pe = 2 .T/ r

where T is the surface tension.

This equation shows that if Pe increases, the nucleation and growth of bubbles is suppressed and so bubbles collapse and disappear.

There are two very practical applications of this result: ?One concerns feeder design. It is often found that these are designed so that their height and diameter are approximately equal, whereas it would be better to make feeders thinner and taller to increase their H/D ratio to 1.5 or 2. This provides a slight pressurisation to the solidifying metal, equal to .·g·H, where . is the density, g the acceleration due to gravity and H the head of metal.

?The other is the location of feeders which should always be placed at the highest point on the casting if they are to be most effective.



Rule No. 6: The Pressure Gradient Requirement

There must be sufficient pressure differential:

- to cause the feed metal to flow, and
- the flow must be in the correct direction.

Driving force = Positive pressure + negative pressure

❑ Positive:
Atmospheric (P_{at}) + hydrostatic (P_{hyd}) pressures

❑ Negative:
Generated by solidification of liquid metal (P_s)

Net pressure must be
higher in the feeder than the casting.

6) Pressure Gradient Requirement

The sixth rule (**Figure 3206.00.07**) is the Pressure Gradient Requirement and is similar to Rule 5. It can be simply stated as:

"There must be sufficient pressure differential to cause the feed metal to flow and the flow must be in the correct direction."

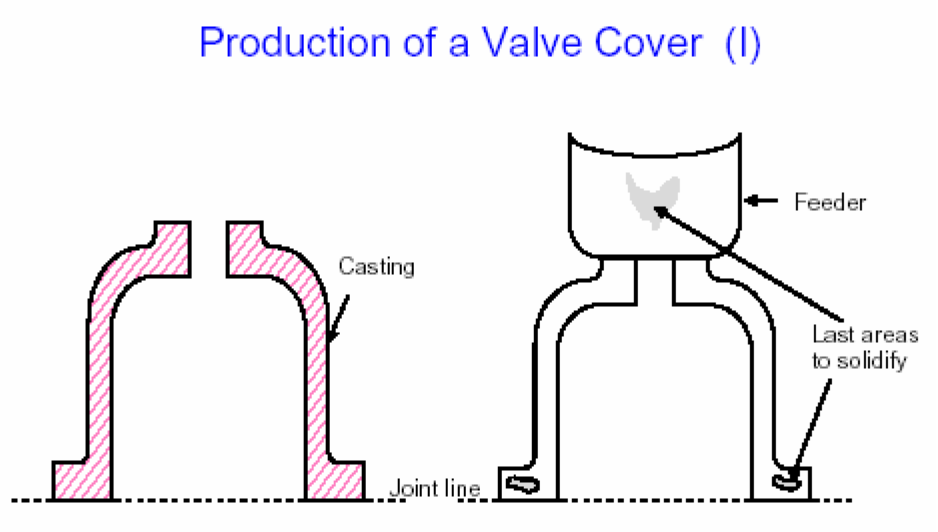
The driving force for the flow of the feed metal is the sum of two pressures:

1. A positive pressure - from atmospheric pressure on the metal and the hydrostatic head in the feeder; and
2. A negative pressure - generated within poorly fed regions as the liquid metal contracts within a solid shell.

These driving forces are additive: the feed metal flows as a result of being pushed from the outside and pulled from the inside. It should be clear that the net pressure must be higher in the feeder than in the area of the casting which is being fed.

Valve Cover Example

This rule is best illustrated by giving a practical example (**Figure 3206.00.08**). This concerns a valve cover casting (which is shaped rather like a bell jar), with a heavy section at the top, a heavy section flange and a thin wall connecting the two. In other words, there are two isolated heavy sections and it is likely that both will need to be fed if they are to be produced free from shrinkage porosity. The initial option to be considered would be to place a feeder on the top of the casting. Assuming that this is correctly designed, it should be capable of compensating for the shrinkage in the heavy section at the top of the casting, so that this area of the casting should be quite sound. However, it does not take too much imagination to predict that the thin walls will solidify relatively rapidly, cutting off the path between the feeder and the bottom flange. The last areas to solidify are shown and it can be clearly seen that shrinkage cavities in the bottom flange would be expected. This means that a feeder is also required on this flange.

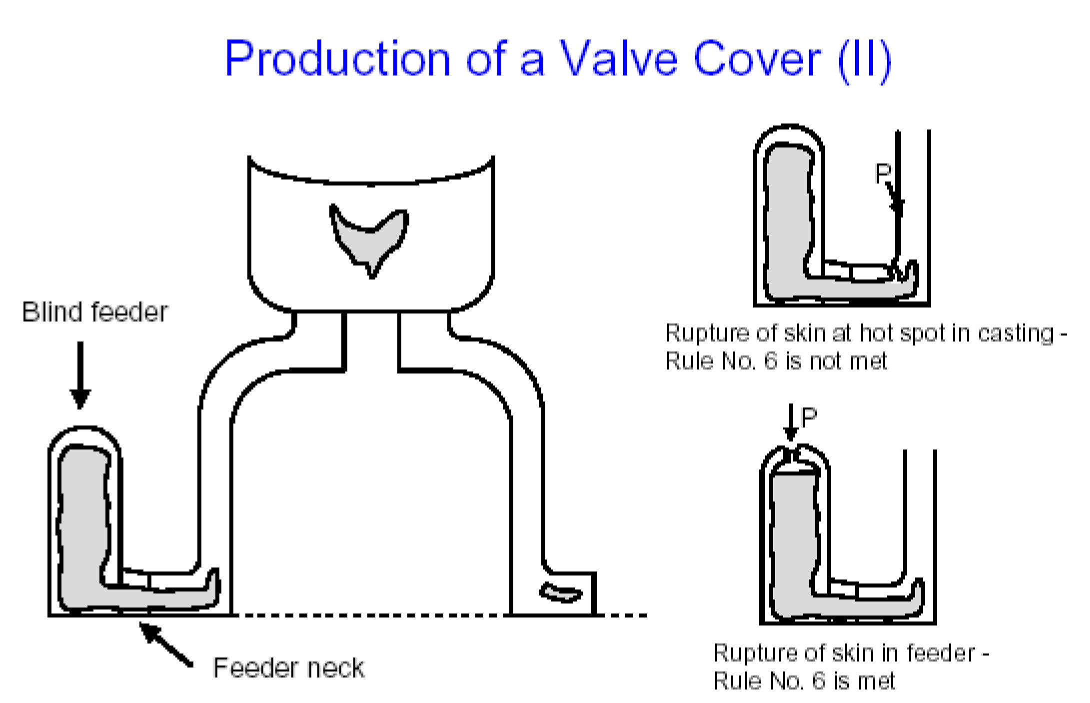


One alternative would be to use a 'blind' feeder as shown in **Figure 3206.00.09**. This is called 'blind' because it is not open to the atmosphere. As the metal in the feeder starts to solidify, a solid skin is first formed which becomes progressively stronger as the temperature falls. As further solid forms, the volumetric contraction results in a hydrostatic tensile stress in the remaining liquid, and the internal suction causes the whole of the solidifying area to start to collapse inwards. This plastic collapse continues for a while, but eventually it is likely that the internal stress will be relieved by either a

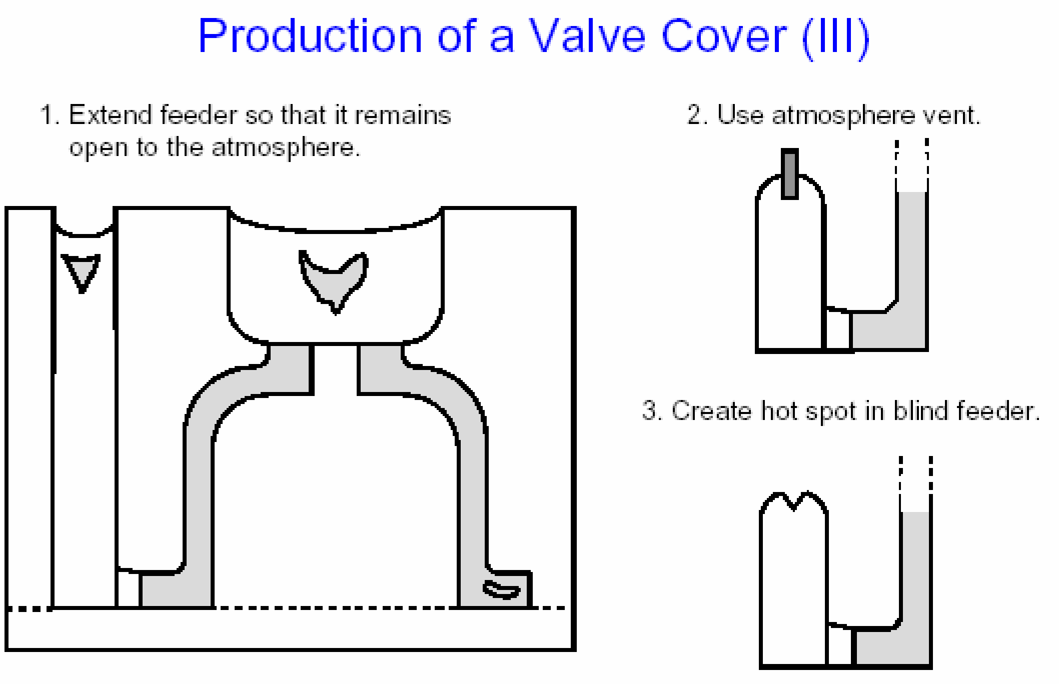
fracture in the skin or nucleation of an internal pore. This may occur in either the casting or the feeder, with very different results:

If fracture occurs towards the top of the feeder, atmospheric pressure will be able to act on the molten metal remaining in the feeder. This creates a pressure differential which is in the correct direction to cause molten metal to flow from the feeder to the shrinkage area in the casting, thus satisfying Rule Number 6 - The Pressure Gradient Requirement.

On the other hand, if the casting design is such that there is a hot spot in the vicinity of the last area to solidify, the hydrostatic tensile stress in the liquid is likely to cause rupture of the casting skin at the hot spot. Hence, atmospheric pressure is now acting on the liquid area in the casting, with the result that the pressure gradient is away from the casting to the feeder, which will cause the metal will flow from the casting into the feeder! In this case, Rule Number 6 is not met. The resulting casting will be more porous than if no side feeder had been used at all.



One way to overcome this problem is to ensure that the feeder remains open to the air so that atmospheric pressure acts on the feeder (**Figure 3206.00.10**). This would require the feeder to be extended upwards, which is not always easy to do. In addition, it reduces the yield.



An alternative approach is to use an atmospheric vent which is a sort of porous plug to let in air and maintain a positive pressure in the feeder. However, one word of caution: in small castings, especially when the metal has low superheat, the porous plug may cool the feeder, leading to solidification around the plug, and thus sealing it closed. Yet another solution is to create a hot spot in the feeder by placing a notch on its top surface. This serves to delay the formation of a solid skin on the feeder - or if one does form, the notch will ensure that it is more readily ruptured. Nevertheless, care is still needed since although such solutions generally work well for large feeders, they tend to be unreliable in small feeders.

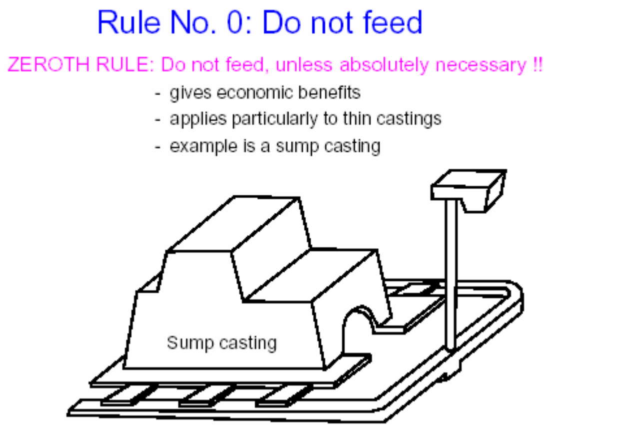
7) The Zeroth Rule

Figure 3206.00.11 summarises the Six Feeding Rules that I have introduced to you so far. Hopefully you will now appreciate that there are many pitfalls in setting up a feeding system for a casting although, if attention is paid to all of these rules, it is normally possible to produce a sound casting.

Summary of the Seven Feeding Rules

Rule 1: The heat transfer requirement.
Rule 2: The volume requirement.
Rule 3: The junction requirement.
Rule 4: The feed path requirement.
Rule 5: The pressure requirement.
Rule 6: The pressure gradient requirement.

However, the difficulties inherent in devising a good feeding system lead one to suggest that there should be an additional rule - The Zeroth Rule (**Figure 3206.00.12**) – which states that **you should not feed a casting unless it is absolutely necessary**! This is perhaps rather surprising but it does overcome the otherwise common problem of designing an effective feeding system. Elimination of feeding also brings economic benefits, such as an improved yield and reduced fettling since it is no longer necessary to cut the feeder off the casting. This rule can often be applied when thin astings are concerned and, for example, the sump casting shown here (which you have seen previously) was produced without any feeders.



Rule No. 0: Do not feed

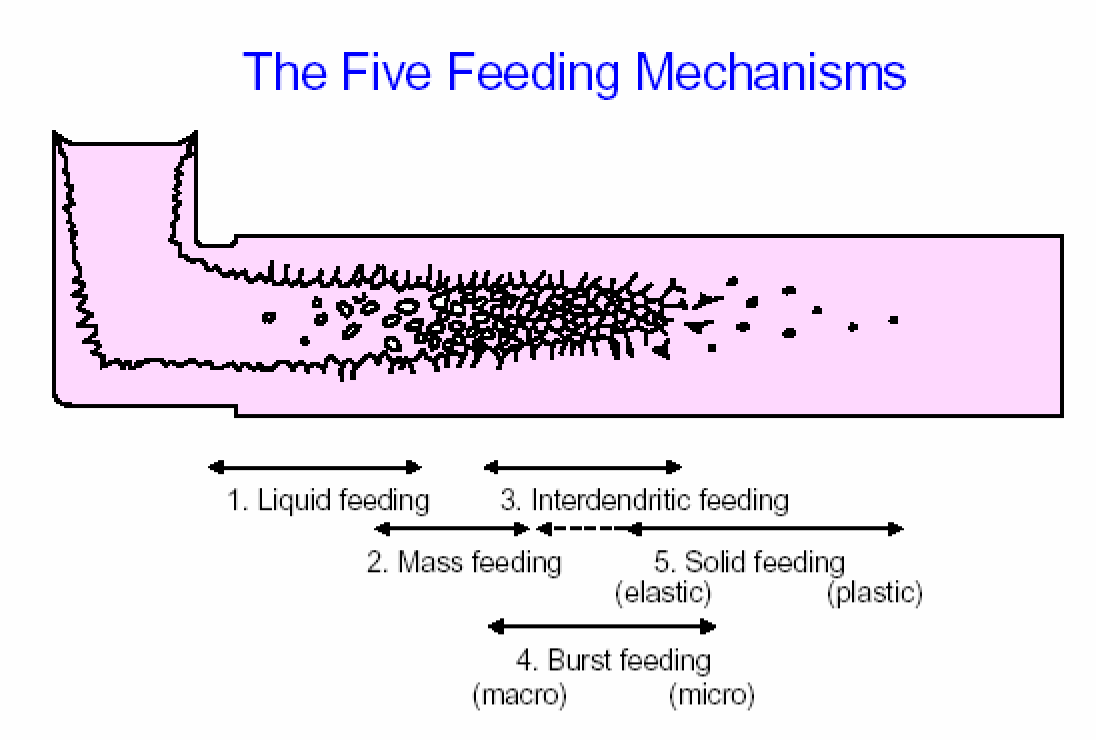
ZEROTH RULE: Do not feed, unless absolutely necessary !!

- gives economic benefits
- applies particularly to thin castings
- example is a sump casting

Summary of the Seven Feeding Rules

Rule 1: The heat transfer requirement.
Rule 2: The volume requirement.
Rule 3: The junction requirement.
Rule 4: The feed path requirement.
Rule 5: The pressure requirement.
Rule 6: The pressure gradient requirement.
Zeroth Rule: Do not feed unless absolutely necessary!

The Five Feeding Mechanisms

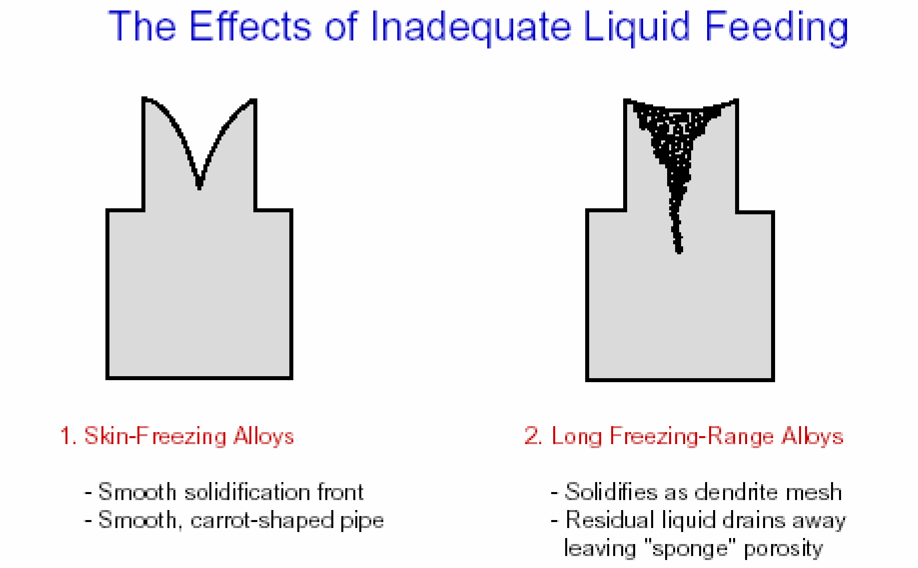


I would now like to turn to the five feeding mechanisms which are listed in **Figure 3206.00.14** and also shown schematically. As the casting solidifies, the demand for feed liquid in the centre of the casting becomes progressively more difficult to meet, as tangles of dendrites obstruct the feed channels, or regions of liquid become actually cut off from the source of feed metal. This increasing feeding difficulty causes the pressure in the centre of the casting to fall, possibly falling so far as to become negative in some cases, as a hydrostatic tension. The generation of large hydrostatic tensions in the interior of casting is undesirable, since it constitutes the driving force for the nucleation and growth of pores (either shrinkage or gas) and a driving force for the inward collapse of the casting which might be revealed as a surface sink. The action of the various feeding mechanisms is to provide material - which can be either liquid or solid - which will flow under the growing pressure gradient, so as to compensate for the volume deficit resulting from the transition from liquid to solid. In so doing, the pressure gradient is reduced thus reducing the driving force for the creation of internal porosity or external sinks. There are five main mechanisms which can be identified by which feeding can occur. These are dealt with here in the order in which they might occur in a real casting, although not all need occur in any one casting. The order will be seen to progress from 'open' systems to 'closed' feeding systems.

1) Liquid Feeding

- Most "open" type of feeding mechanism
- Generally occurs first
- Normally the only feeding mechanism in skin-freezing alloys
- Works well with low pressure gradients
- Governed by the Seven Feeding Rules

The first mechanism is *Liquid Feeding* (see **Figure 3206.00.15**). This is the most 'open' of the feeding processes, and generally precedes other forms of feeding. It can be noted that in skin freezing materials - such as pure metals and eutectics - it is the *only* type of feeding process. Since the liquid metal has such low viscosity (near to that of water) this mechanism works effectively at negligibly small pressure gradients. For all practical purposes therefore, if liquid feeding can be ensured in a particular casting, then the stresses which can occur in the liquid will be maintained at such a low level that no practical difficulties will be found. The rules for adequate liquid feeding are the Feeding Rules described at the beginning of this lecture.



Where inadequate liquid feeding has been applied, i.e. where the feeder has run dry part way through the freezing of the casting, then two types of porosity are found (see also **Figure 3206.00.16**):

1. Smooth-sided shrinkage pipe:

skin-freezing alloys will solidify with a smooth solidification front, so that a shrinkage cavity will expand, eventually to be constrained by the inward growth of the smooth freezing front. Thus the shrinkage pipe will be the classical smooth carrot-shaped cavity.

2. Shrinkage pipe in the form of sponge porosity:

long freezing range alloys will normally freeze as a tangled mass of dendrites, so that if the feed liquid is in short supply, then the dendrite mesh can drain of interdendritic liquid, with the result that the shrinkage pipe from the feeder forms an extensive sponge. The shrinkage pipe still is in the form of a single cavity, but its appearance is now complicated by its shape. If a transverse section is made, the porosity appears to be a series of hundreds or thousands of separate minute pores, and is thus often mistaken for microporosity, when it is in fact a single macropore. This type of shrinkage sponge is particularly damaging for castings which are required to be leaktight after machining.

2) Mass Feeding

The second feeding mechanism is known as *Mass Feeding* (**Figure 3206.00.17**). This is the term used to denote the flow of a slurry of liquid plus solid crystals. It can occur up to about 68 % solid in some alloys. At that stage of freezing the dendrites start to impinge to form a coherent network, as a three dimensional space frame, thus gaining rigidity and resistance to further deformation.

Mass Feeding

- Flow of slurry of solidified metal in residual liquid
- Can occur up to ~ 68 % solid
- Improves as: - section size increases
- grain size decreases
- Can effectively counter the development of layer porosity

The action of mass feeding is sensitive to the relative size of the grains and to the section thickness of the solidifying casting. For instance mass feeding cannot act in thin section castings which have not been grain refined. Mass feeding improves as section thickness increases and as grain size becomes smaller. Thus is simply because if the section is narrow and if the grains are large, they impinge on each other and are supported on the side walls of the casting, and so are not free to move. Porosity in such sections occurs because of the difficulty of flow of the liquid among the dendrite mesh: this is typically layer porosity - a kind of shrinkage porosity which grows among the fixed network . As the section size grows and grains become smaller so this constraint disappears, and the interior semi-solid slurry is free to flow, thus more easily feeding the more distant regions of the casting. Layer porosity effectively disappears in such sections. From the point of view of the casting technologist, grain refinement is clearly an important way of facilitating this feeding mechanism.

3) Interdendritic Feeding

The third Feeding Mechanism is *Interdendritic Feeding* (**Figure 3206.00.18**). As the dendrite mesh thickens, the interdendritic channels become progressively narrower, and progressively more resistant to the flow of the residual liquid. We can gain a useful insight into the mechanism by assuming that the channels can be treated as capillaries. Assuming Poisseuille's famous equation for the flow of liquid along a capillary we have:

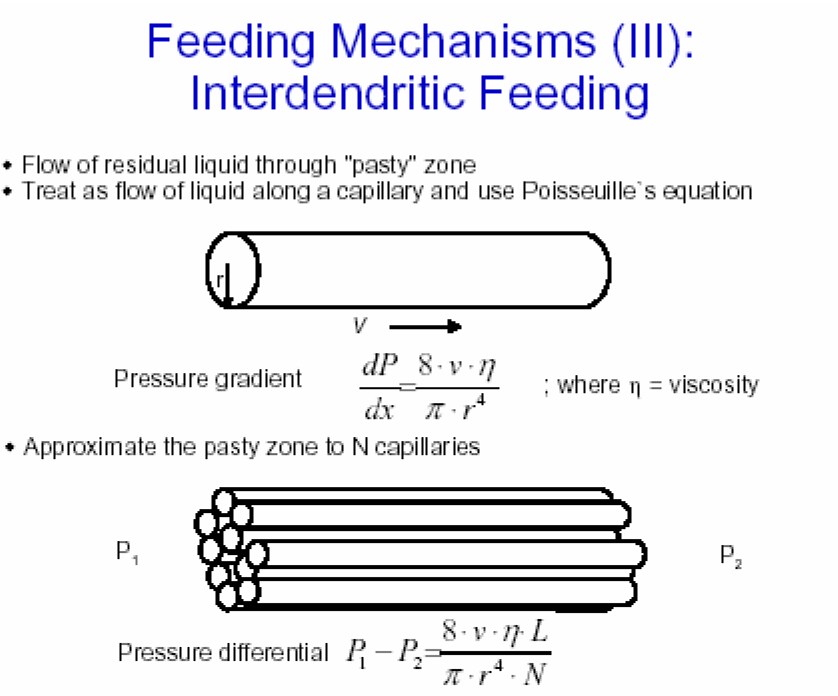
$$\frac{dP}{dx} = \frac{8\,\eta\,v}{\pi\,r^4}$$

where dP/dx is the pressure gradient required to cause the flow,

η is the viscosity,

v is the volume flowing per second,

and r is the radius of the channel.



Feeding Mechanisms (III): Interdendritic Feeding

- Flow of residual liquid through "pasty" zone
- Treat as flow of liquid along a capillary and use Poisseuille`s equation

Pressure gradient $\frac{dP}{dx}=\frac{8\cdot v\cdot\eta}{\pi\cdot r^4}$; where η = viscosity

- Approximate the pasty zone to N capillaries

Pressure differential $P_1-P_2=\frac{8\cdot v\cdot\eta\cdot L}{\pi\cdot r^4\cdot N}$

If now we can assume that the pasty zone can be approximated to a bunch of N capillaries of length L, then the pressure differential across the pasty zone required for flow through the zone is reduced to:

$$P_1 - P_2 = \frac{8\,\eta\,v\,L}{\pi\,r^4\,N}$$

For a particular radius, which corresponds roughly to a given size of final pore, the increase of N by grain refinement is seen to be useful in reducing the pressure requirement. Thus grain refinement seems useful for the improvement of interdendritic feeding also. However, this is a relatively insignificant effect compared to the influence of r, which is raised to the fourth power. Clearly, as solidification continues and as the mesh is finally closing, r becomes extremely small and so the pressure differential required to cause interdendritic flow becomes extremely high: this is when the greatest problems of feeding through the interdendritic mesh occur. The effect of capillary size on the required pressure differential explains the enormous effect of a small amount of eutectic liquid (**Figure 3206.00.19**).

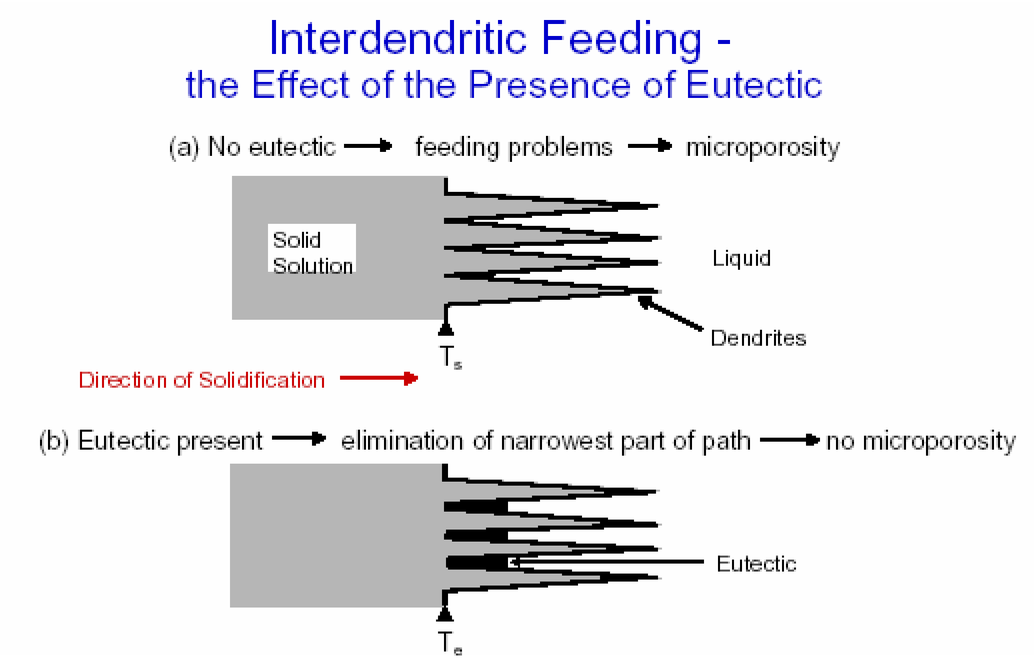


Diagram (a) shows schematically that if there is no eutectic present, then the tapering interdendritic path (towards the root of the dendrites) increases the difficulty of the final stage of interdendritic feeding, where r becomes vanishingly small causing high viscous restraint to flow.Diagram (b) shows that the presence of a per cent or so of eutectic liquid at the roots of the dendrites, as a result of interdendritic segregation, effectively truncates the final, narrowest parts of the channels by solidifying on a planar front when the eutectic isotherm is reached during cooling. The pressure is typically reduced by orders of magnitude by the arrival of just one per cent of eutectic liquid and therefore the last stages of feeding are much easier.As the percentage of an alloying element increases in a alloy, a stage is reached at which the solid solution region is exceeded and eutectic liquid first appears. This point is usually markedly below the composition at which eutectic would be predicted from the equilibrium diagram, and is, of course, the result of non-equilibrium freezing, with solute concentrated into the remaining liquid between the dendrite arms - the interdendritic liquid.

Before the eutectic liquid first appears, the long tapering feeding channels cause a maximum problem for feeding, and so microporosity is the result in such (nonequilibrium) long freezing range compositions. When the alloy content has risen to allow eutectic liquid to appear, then the porosity disappears, to be replaced initially by a maximum in the susceptibility to hot tearing. This rapidly reduces as the alloy content is increased, increasing the percentage of eutectic phase.

4) Burst Feeding

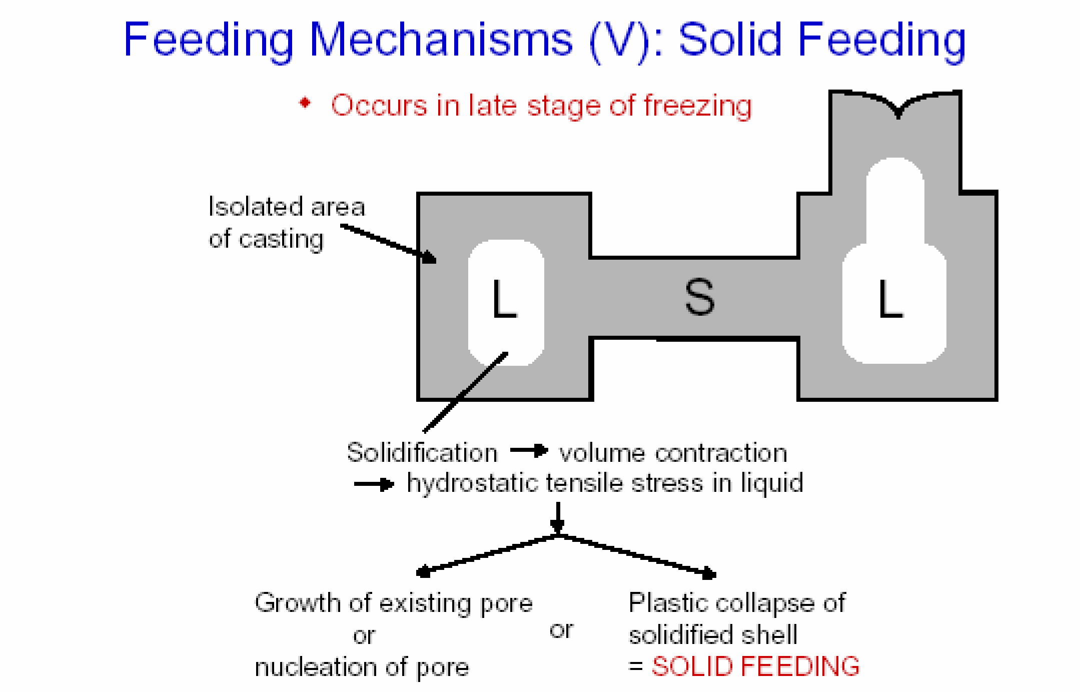
Our fourth mechanism is *Burst Feeding* (**Figure 3206.00.21**). This has been predicted as being possible, but very little evidence has been obtained for it to date. This is perhaps not surprising, since it will be difficult to observe, and difficult to predict since computer models are not yet sufficiently sophisticated. It was proposed to allow for the condition where the build-up of pressure across a barrier to feeding causes the barrier to collapse, allowing an in-rush of feed liquid. Such barriers are envisaged to be meshes of dendrites, perhaps heaped up as a result of mass feeding, especially if this pile-up chokes a narrow feed path into a larger section requiring feed metal.

Burst Feeding:

- Predicted as being possible, but little evidence to date.
- Assume sudden yielding of barrier to feed metal
  in-rush of liquid.
- Barrier could be meshes of dendrites.

In practice it may be that the collapse of such structures will be more gentle than dramatic, as a result of the plasticity of the dendrites at temperatures near their melting point. However, the curved appearance of some types of layer porosity may be the result of such deformation of the dendrite mesh prior to, or perhaps during, the ingress of feed liquid to underfed regions. Burst feeding is perhaps something to be kept in mind as a logical possibility rather than viewed as a mechanism of great importance, or so it seems at this time.

5) Solid Feeding



Feeding Mechanisms (V): Solid Feeding

- Occurs in late stage of freezing

Isolated area of casting

Solidification → volume contraction
→ hydrostatic tensile stress in liquid

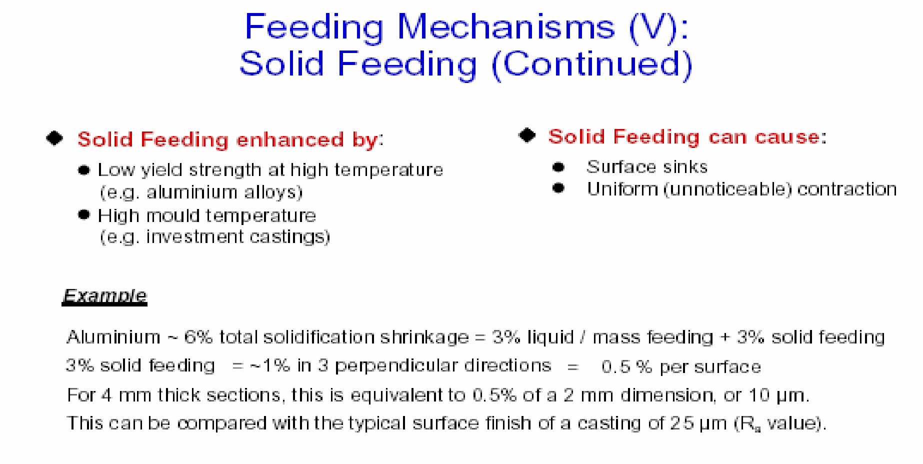
Growth of existing pore or nucleation of pore

or

Plastic collapse of solidified shell = SOLID FEEDING

The final mechanism is *Solid Feeding* (**Figure 3206.00.22**) . In contrast to burst feeding, solid feeding is a mechanism of great importance, and for which there is a great deal of evidence. It is essential to understand this mechanism thoroughly to be able to understand the feeding of real castings. This is the most 'closed' type of feeding. It describes the situation where a region of the casting has become isolated (or effectively isolated) from the supply of feed liquid. As the residual liquid in this region continues to freeze it progressively occupies less space. This space has to be accounted for somehow. One option is for it to grow as a shrinkage or gas pore, although this requires either a pore to be already in place somehow, or a suitable nucleus to be in place to allow a pore to be created. The other option is for the solid shell of the casting to collapse inwards under the internal reduced pressure, so making up the volume deficit. Solid feeding therefore relieves the hydrostatic tensile stress built up in the liquid by the inward flow of the solid.

Figure 3206.00.23: If the yield stress of the solid shell is low, then solid feeding occurs so easily that only limited internal tension can build up. This happens in aluminium alloys, but less readily in steels and high temperature alloys where the poor thermal conductivity of the metal results in a cool and hence strong shell of solidified metal. Solid feeding is also enhanced by the use of high mould temperatures as in investment casting, where moulds are sometimes preheated to temperatures approaching the freezing point of the metal. The solidified shell is especially plastic in such conditions, and, automatically it seems, isolated bosses feed themselves!



Feeding Mechanisms (V):
Solid Feeding (Continued)

- **Solid Feeding enhanced by**:
  - Low yield strength at high temperature (e.g. aluminium alloys)
  - High mould temperature (e.g. investment castings)
- **Solid Feeding can cause**:
  - Surface sinks
  - Uniform (unnoticeable) contraction

Example

Aluminium ~ 6% total solidification shrinkage = 3% liquid / mass feeding + 3% solid feeding

3% solid feeding = ~1% in 3 perpendicular directions = 0.5 % per surface

For 4 mm thick sections, this is equivalent to 0.5% of a 2 mm dimension, or 10 µm.

This can be compared with the typical surface finish of a casting of 25 µm (R_a value).

Collapse of the solid shell to feed internal shrinkage is often seen as sinks on the surface of castings adjacent to a heavy section. However, such undesirable shape deformations need not always accompany solid feeding. If the general plasticity of the solid shell can be kept reasonably uniform then collapse can be so uniform as to be unnoticed. For instance, if we assume that the solidification shrinkage of an aluminium alloy is 6%. The first 3% or more is easily provided by liquid and/or mass feeding. The remaining 3%, if isolated from outside supplies of feed metal, now has to be spread over 3 perpendicular directions, i.e. 1% in each direction. If this is further spread over opposite surfaces, then this is 0.5% per surface. For a 4 mm cast section this is 0.5% of a 2 mm dimension, or 0.01 mm, which is effectively unmeasurable on most castings, being smaller than the surface roughness of most sand and gravity die castings. It is important to note that solid feeding is assisted by atmospheric pressure, but not necessarily dependent on it. For instance it can work effectively in vacuum castings. Finally, solid feeding will also operate at a late stage of freezing even if the region is not entirely isolated from the liquid supply. The gradual build up of hydrostatic tensile stress in the residual liquid as interdendritic feeding occurs can rise to such a level that the stress becomes limited by the collapse of the surrounding solid. In this case it is clear that interdendritic feeding can take place at the same time as solid feeding - both are cooperating in an attempt to reduce the internal stress in the poorly-fed region. In conclusion, this lecture has examined how the shrinkage inherent in making a casting is compensated for by the use of feeding. We have considered both the mechanisms by which feeding takes place and the rules that need to be followed if we are to produce sound castings. Feeding is not always easy to get right and failure inevitably leads to the initiation of shrinkage porosity.