MME 345

Lecture **B:07**

The Design of Feeding Systems

1. Requirements and necessity of feeding

Ref:

[1] P. Beeley, Foundry Technology, Butterworth-Heinemann, 2001

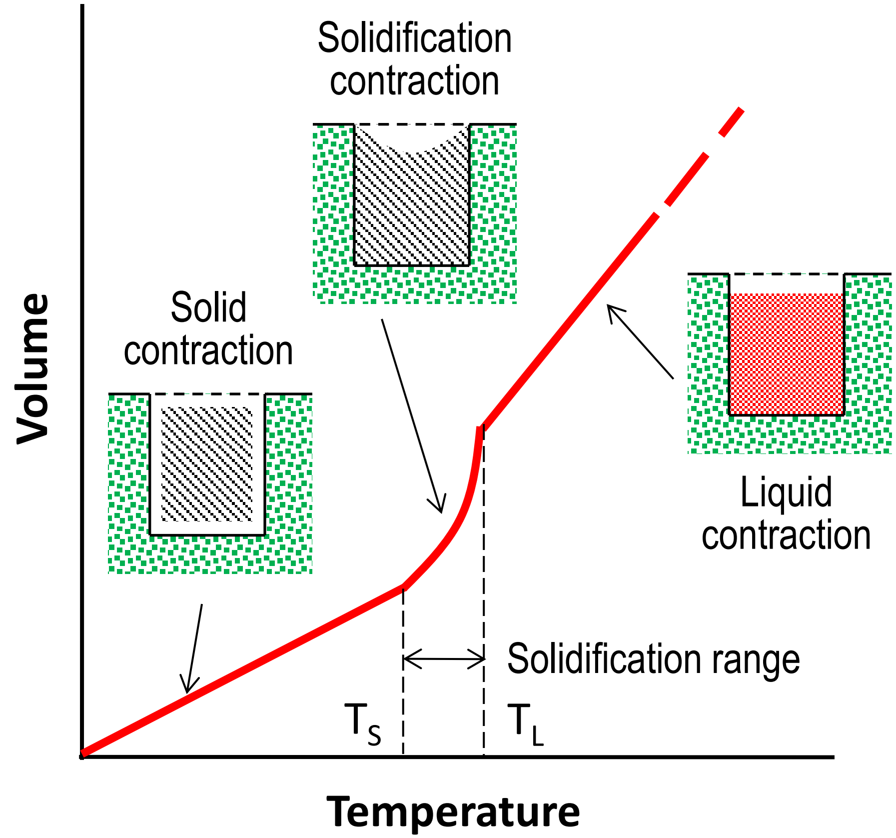
[2] J. Campbell, Castings, Butterworth-Heinemann, 2001

Topics to discuss….

1. General shrinkage behaviour
2. Classification of feeder
3. Feeding rules
4. Shrinkage porosity

1. General Shrinkage Behaviour

- Molten metal occupies considerably more volume than the solidified casting
- Thus, during solidification liquid suffers volume contraction, which, if not attended, can create many problems
- Liquid metals experience **THREE** different contractions during solidification:
  1. **Liquid contraction**
     not troublesome
  2. **Solidification contraction**
     causes feeding problem
  3. **Solid contraction**
     causes hot tearing/cracking



schematic illustration of three shrinkage regimes: in the liquid, during freezing, and in the solid

- Once pouring is complete, the original supply of liquid metal is removed.

  Thus, some source of molten metal must be provided to feed the shrinkage that occurs as the metal cools in the mould.

- In some cases, especially with small castings, the gates and runners can be designed so that they are able to feed the shrinkage.

  Sometimes, gates are also used to scatter shrinkage, distributing it so that shrinkage at any one point is slight and the soundness of the casting is not appreciably affected.

- Sometimes, heavy sections of a casting can feed light or thin sections.

- In most cases, however, we must use external liquid reservoirs called **feeders / risers,** to supply molten metal to the casting after pouring.

- If properly used, the **feeder will feed shrinkage** even while solidification is going on.

  In other words, it will feed both liquid shrinkage and solidification shrinkage.

Feeding characteristics of alloys

- Liquid contracts on freezing because of **rearrangement of atoms** from open "randomly-packed" structure to a regular "densely-packed" structure.

- FCC and HCP solids contract more during solidification.

Metal	Crystal Structure	Volume Change, %
Al	fcc	7.14
Cu	fcc	5.30
Mg	hcp	4.10
Zn	hcp	4.08
Fe	bcc	3.16
Li	bcc	2.74
Si	diam	-2.90
Bi	rhom	-3.32

FCC /HCP materials:

3.2 – 7.2 % contraction

BCC materials:

2.0 – 3.2 % contraction

Some materials "expand" during solidification.

Example: Water, Si, Bi, Grey cast iron

- Based upon the major contrasts in solidification behaviour, **three types** of alloys groups can be recognised.

Group 1: Short freezing range alloys

- Low carbon steels
- Brasses
- Aluminium bronze
- High tensile brass
- Aluminium
- Copper

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- **freezing with marked skin formation**
- **directional solidification favoured; extremely sound casting with large shrinkage cavity**

Group 2: Long freezing range alloys

- Medium and high carbon steels
- Nickel base alloys
- Phosphor bronzes
- Gunmetals
- Magnesium alloys
- Complex aluminium alloys

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- **showing extensive pasty zones during freezing**
- **directional solidification not favoured unless heavy chill/large temperature gradient used; casting with widespread gas and shrinkage porosity**

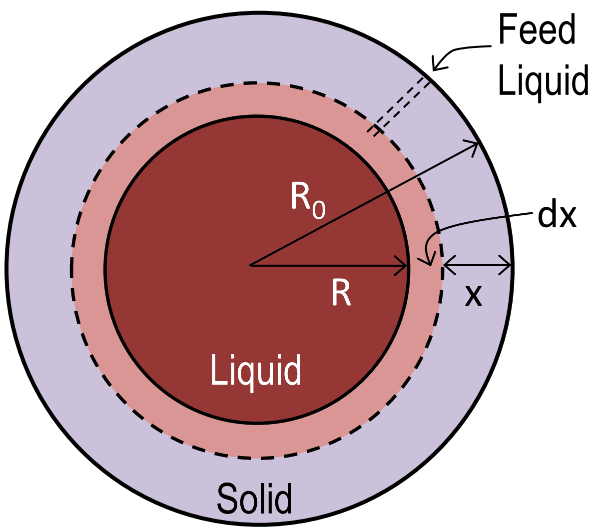
Group 3: Alloys having expansion stage

- Grey cast irons
- Ductile cast irons

→

- **undergoes two successive stages of freezing: contraction during formation austenite dendrite (as in Group 2), and expansion during transformation of eutectic with precipitation of graphite.**
- **for rigid moulds, expansion of stage 2 offsets the contraction of stage 1.**
- **in most cases, the positive pressure of stage 2 dilates the mould and creates a demand for feed metal, giving susceptibility to internal porosity on further cooling**

What happens to a poorly fed casting?



solidification model for an unfed sphere-shaped casting

- ❑ Source of feed metal is cut off after a solid shell of thickness ***x*** is produced.
- ❑ What will happen during solidification of the next onion-layer of thickness ***dx*** ?

- **Either a pore will form or the liquid will expand a little and the solid x will contract a little to compensate the volume difference.**
- **If no favourable nucleus available for pore formation, the liquid has to accommodate this by expansion, creating a state of tension or negative pressure and sucking the solid shell inwards.**

- ❑ As more onion layers form, the tension in the liquid increases, the liquid expands, and the solid shell is drawn inwards.
- ❑ Eventually, the pressure becomes large enough for the pasty liquid and the casting collapses by plastic or creep flow and forms shrinkage cavity

- Whether the **driving force for pore formation** wins over the **driving force for feeding** will depend on whether nuclei for pore formation exist.
- If not (i.e. the metal is clean), then pore will not be able to nucleate and feeding is forced to continue until the casting is completely frozen.
- If favourable nuclei are present, then pores will be created at an early stage before the development of any significant hydrostatic pressure, with the result that little feeding will occur and the casting will develop its full percentage of porosity as defined by the physics of phase change.

- In most practical cases, the situation is somewhere between these two extremes, with castings displaying some internal porosity, together with some liquid feeding.
- In such cases feeding will continue under increasing pressure differences, until the development of a critical internal stress at which some particular nuclei, or surface puncture, can be activated at one or more points in the casting. Feeding is then stopped at such locality, and pore growth starts.

When pores appear early

- For a 100 mm diameter sphere casting, size of shrinkage cavity formed due to freezing contraction is shown in the table.
- Theses considerable cavities require a dedicated effort to ensure that they do not appear in castings

Freezing contraction	Diameter of shrinkage cavity
3 vol.% (Fe)	**31** mm
7 vol.% (Al)	**41** mm

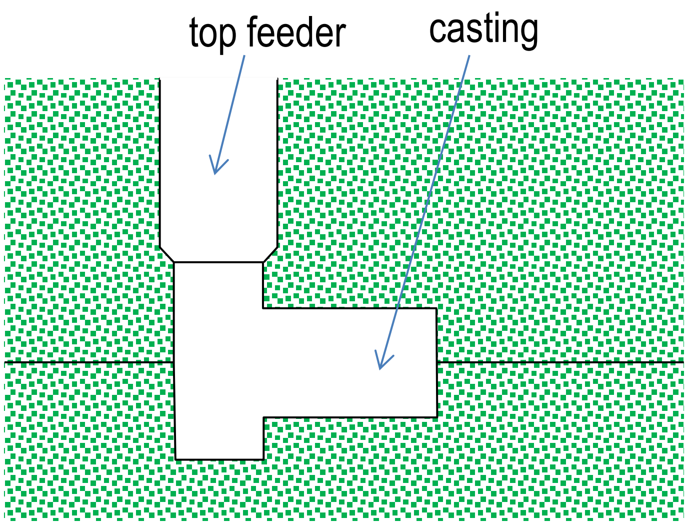
There are occasions when castings having defects of only 1 or 2 mm in size are scrapped!!

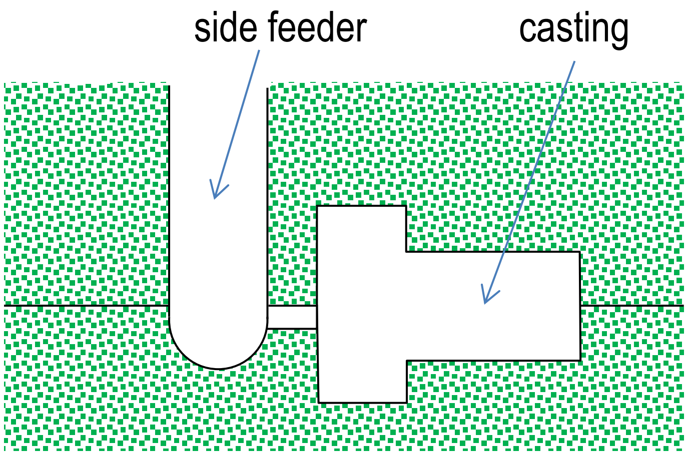
- For the vast majority of cast materials, **shrinkage porosity** is common and most important defect in castings
- Reducing/removing shrinkage porosity:
  1. **Clean melt**
  2. **Effective feeding**

2. Classification of Feeder

- Although feeders can take several shapes and sizes, there are normally only **two types**. These are named according to their position on the casting.

- A **top feeder** is attached to the top of the casting, while a **side feeder** is attached to the side of the casting

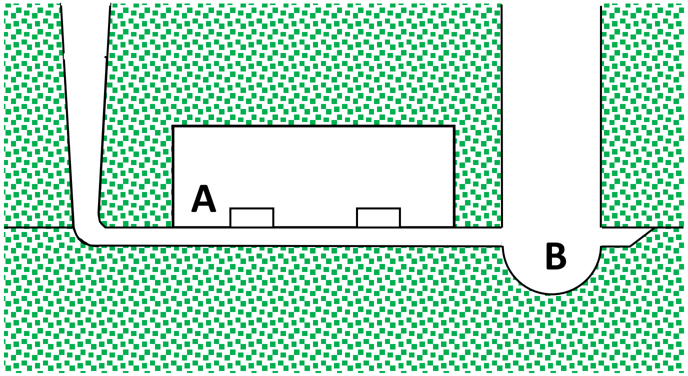




- As far as **location** is concern, we can place a feeder **upstream** from the casting, so that the metal must flow through the feeder to get to the casting,

OR

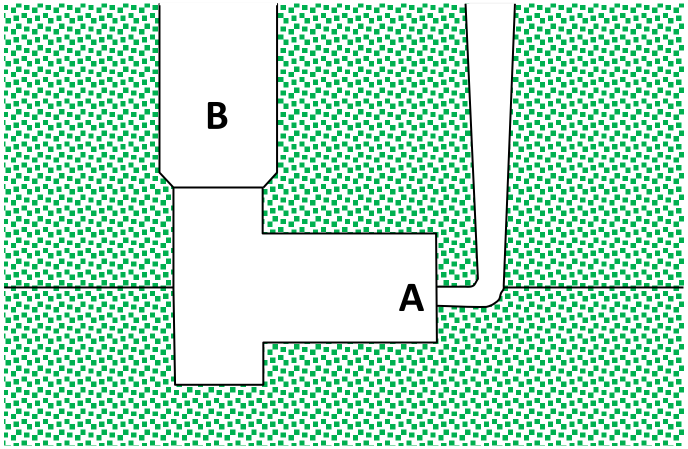
we can put it **down stream**, so that the metal must flow through the casting to get to the feeder.



- When a feeder is set downstream from the casting, it is called a **cold** or **dead** feeder.

As the liquid metal flows through the mould cavity, it gives up some of its heat to the wall of the mould

So when pouring is completed, you will find the hottest metal at point A and the coldest metal at point B.



- Since a cold/dead feeder contains the coolest liquid in the system, it could very well **solidify before the casting** and will not be able to feed the shrinkage.

- So, ideally, the feeder should be located **upstream** from the casting.

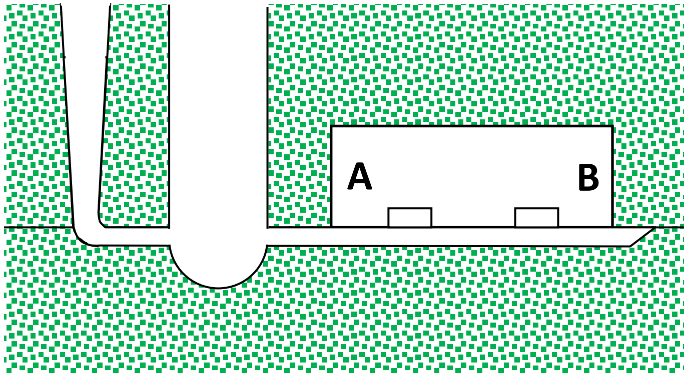
  This way the liquid will have to flow through the feeder to get to the casting.

- A feeder located upstream from the casting should still be as close to the casting as possible.

  So the best place for it is right in the gating system itself.

- A feeder located in the gating system before the casting is called a **hot** or **live** feeder.

  In this case, the metal in the casting will be cooler than the metal in the feeder.



- Thus, the feeder remains liquid longer and promotes **directional solidification**.

  Solidification begins at point B of the casting and ends at point A

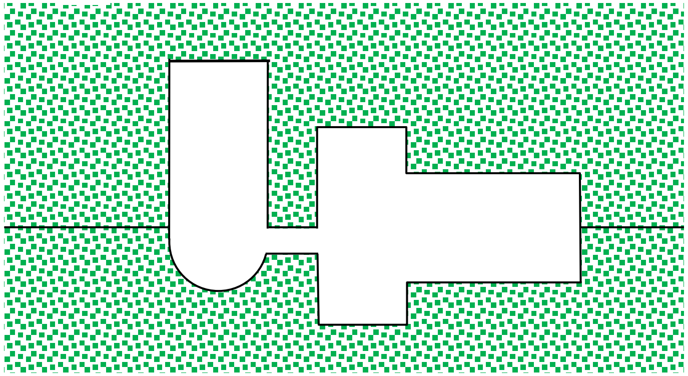
- It is difficult and, in most cases, not a good idea to place a hot feeder at the top of casting. Sometimes, you won't be able to use a hot feeder at all; the conditions will require the use of a cold feeder.

  In such cases we have to use some other means to help keep the feeder liquid.

- When a feeder is **open** to the air,
  heat loss through convection and radiation cannot be avoided.

- To overcome this, foundrymen often use some **insulation** at the top of the feeder.
  Sometimes you will find someone is throwing dry sand on the top surface of an open feeder to serve as an insulation.

- To some extent, this will reduce heat loss.
  But we can go a step further and improve on this practice by designing a feeder so that it is not exposed to the air at all. This type is called a **blind feeder**.
  The sand above this blind feeder is not perfectly insulating, but it does help keep the feeder liquid for an extended period of time.



blind feeder

3. Feeding Rules

1. Do not feed (unless necessary)
2. Heat transfer requirement
3. Volume requirement
4. Junction requirement
5. Feed path requirement
6. Pressure differential requirement
7. Pressure requirement

Rule 1: Do not feed (unless necessary)

- Perfectly applicable to most thin-walled castings.
  - **addition of a feeder on top of a thin walled casting causes problem**
  - **solidification begins during pouring and the casting effectively being fed by the filling system, no additional feeder is necessary**

- Probably 50 per cent of small/medium sized castings do not need to be fed.
  - **modern castings are being designed with progressively thinner walls**

- The remainder of casting that do suffer some feeding demand, many could avoid the use of a feeder by the judicious application of chills or cooling fins.

- This still leaves a reasonable number of castings that have heavy sections, isolated heavy bosses or other features which cannot easily be chilled and thus need to be fed.

Rule 2: Heat Transfer Requirement

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

$$t_f = C\left(\frac{V}{A}\right)^2$$

$$m_F > 1.2\ m_C$$

(as a safety measure, feeder size is increased by 20%)

- ❑ The **modulus**, m (=V/A ratio), of a feeder can be artificially increased by
  - **use of an insulating or exothermic sleeve**
  - **application of insulating or exothermic powder on top of feeder**

Example:

- **A cylindrical feeder in an insulating material is only 0.63D in diameter compared with the diameter D in sand.**
- **This particular insulated feeder therefore has only 40% of the volume of the sand feeder**

Rule 3: Mass Transfer Requirement

"The feeder must contain sufficient liquid to meet the volume contraction requirements of the casting"

- When requirement 2 is satisfied, the volume requirement is not automatically satisfied.
- Although we may have provided a feeder of such a size that it would theoretically contain liquid until after the casting is solid, in fact it may still be too small to deliver the volume of feed liquid that the casting demands.
  - **Normal feeders are relatively inefficient in the amount of feed metal that they are able to provide.**
  - **This is because they are themselves freezing at the same time as the casting depleting the liquid reserves of the reservoir.**

$$\varepsilon V_F = \alpha (V_C + V_F)$$

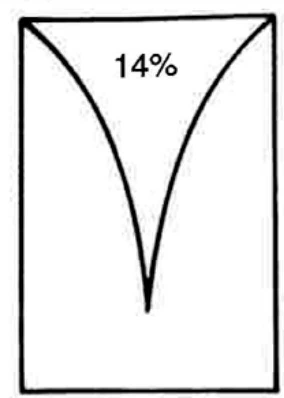
$$V_F = \left(\frac{\alpha}{\varepsilon - \alpha} \right) V_C$$

V_C = volume of casting
V_F = volume of feeder
ε = efficiency of feeder
α = volume thermal expansion coef.

For aluminium alloys castings

α = 7 % ➔ $V_F = V_C$

Maximum yield is 50% !!



H = 1.5 D

Cylindrical feeder of dimension H = 1.5D has the feeding efficiency of only 14% !

For steel alloys castings

FCC alloys: α = 4 %

$$V_F = 0.40\, V_C$$

BCC alloys: α = 3 %

$$V_F = 0.27\, V_C$$

Compared to Al alloys, the smaller solidification shrinkage of ferrous metals reduces the volume requirement of the feeder considerably

- ❑ For graphitic cast irons, the feed volume reduces **approximately zero** in the region of 3.6 to 4.0 % carbon equivalent (CE).
- ❑ A feeder may still be required, because of the difference in timing between the feed demand and the graphite expansion

Rule 4: Junction Requirement

"The junction between the casting and the feeder should not create a hot spot"

1. Feeders and ingates should not be planted on top of the casting so as to create a T- or an L-junction.

   They are best added as extensions to a section, as an elongation to a wall or plate, effectively moving the junction off the casting.

2. If there is no alternative to the placing of the feeder directly on the casting, avoid hot spot in the middle of the junction.

   T – Junction: $m_F > 2\ m_C$

   L – Junction: $m_F > 1.33\ m_C$

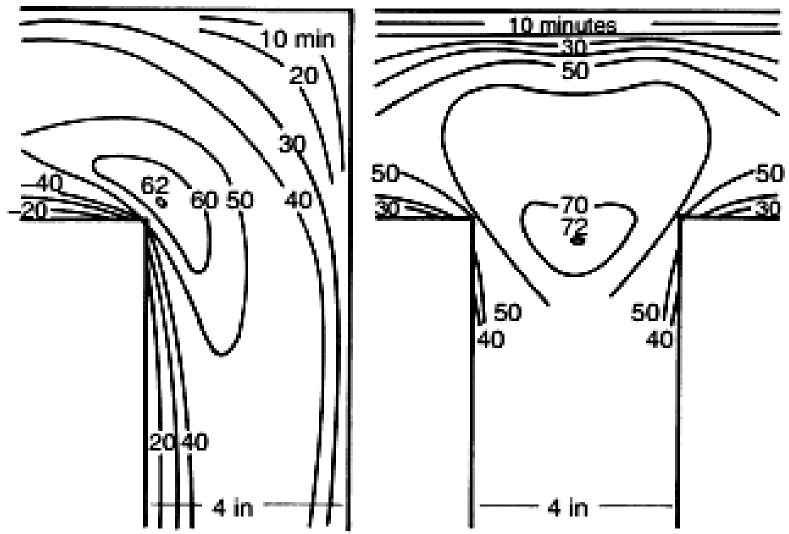


Figure 3.5 Effects of external and re-entrant corners on local rates of freezing: end of freeze waves after successive intervals (from Brandt *et al*[30]) (courtesy of American Foundrymen's Society)

Reducing junction effect by design modification and use of chill

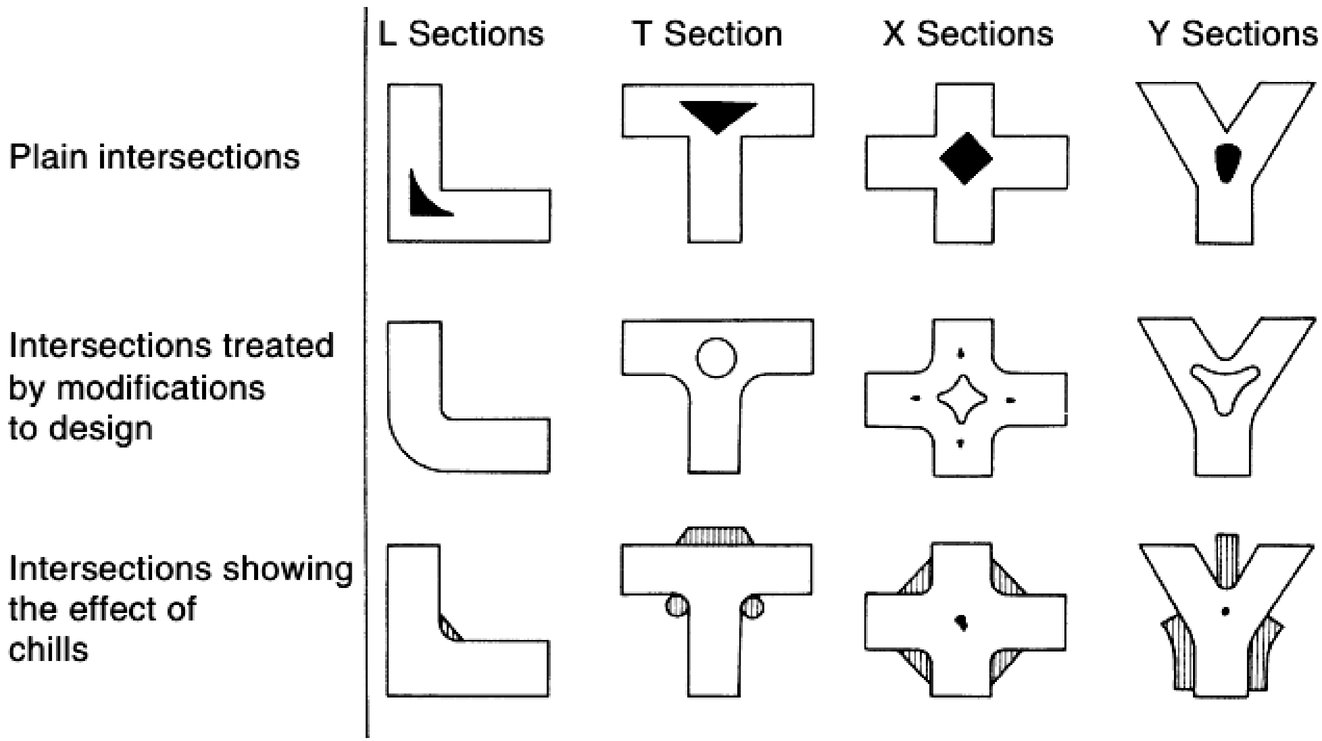


Figure 3.37 Treatments of intersections by design modifications and use of chills (from Briggs *et al*[88]) (courtesy of American Foundrymen's Society)

Rule 5: Feed Path Requirement

"There must be a feed path
to allow feed metal to reach those regions that require it"

- The highest-modulus regions in a casting are either potential regions for shrinkage porosity if left unfed, or may be feeding paths.

- Ways to ensure feed path:

1. **Directional solidification towards feeder**
2. **Minimum temperature gradient**

   when the temperature gradient at the solidus falls to below a critical value (0.1 – 2 K/mm) then porosity is observed even in well degassed material

3. **Feeding distance**

   there will be a limit to how far feed liquid can be provided along a flow path

Ensuring feeding path by a method of 'inscribed circle'

- If the circle diameters (for 2D) or the casting modulus (3D) increase progressively towards the feeder then the condition for directional solidification is met.
- the provision of extra metal on the casting to thicken the section is known as padding.

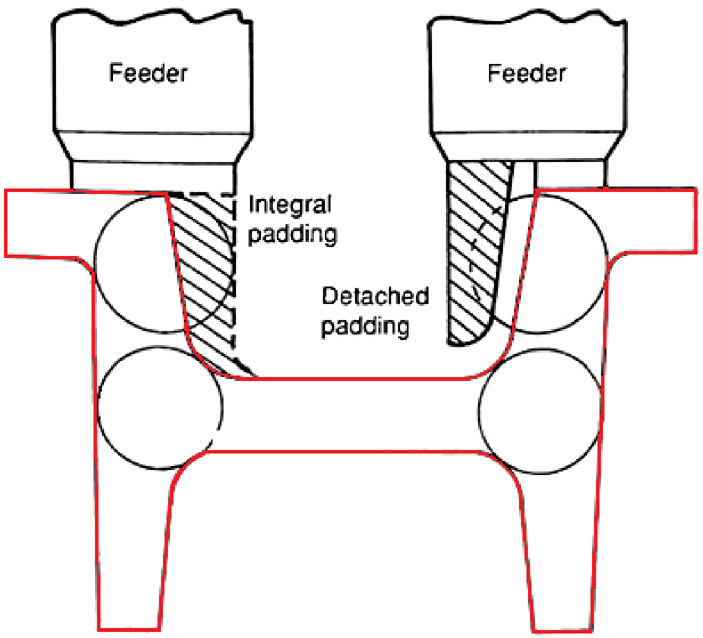


Figure 6.7 *Use of Heuvers circles to determine the amount of attached padding (Beeley 1972) and the use of detached (or indirect) padding described by Daybell (1953).*

Use of indirect pad to promote feeding

- In this indirect padding technique molten metal is fed to a position adjacent to the critical section, thereby delaying the freezing of neighbouring area of the casting.

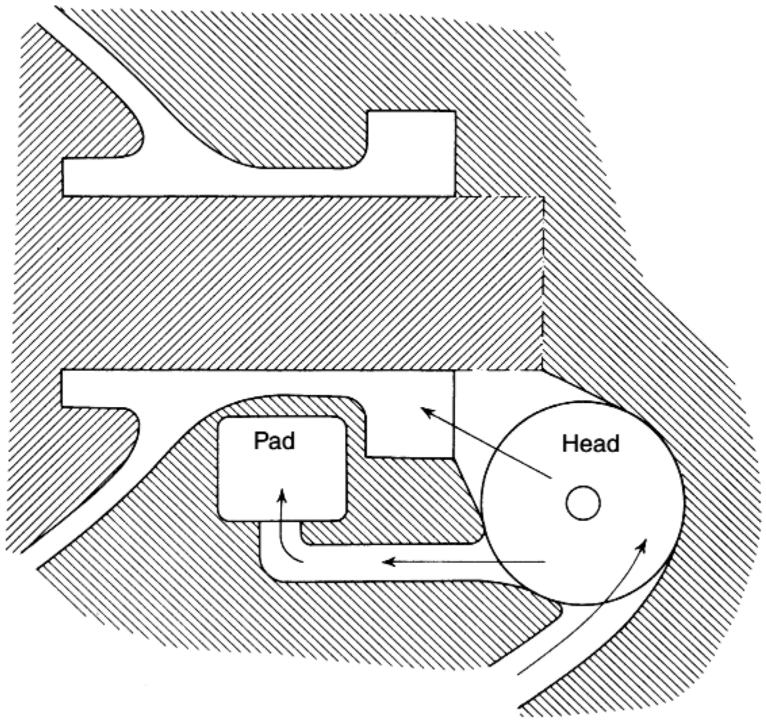


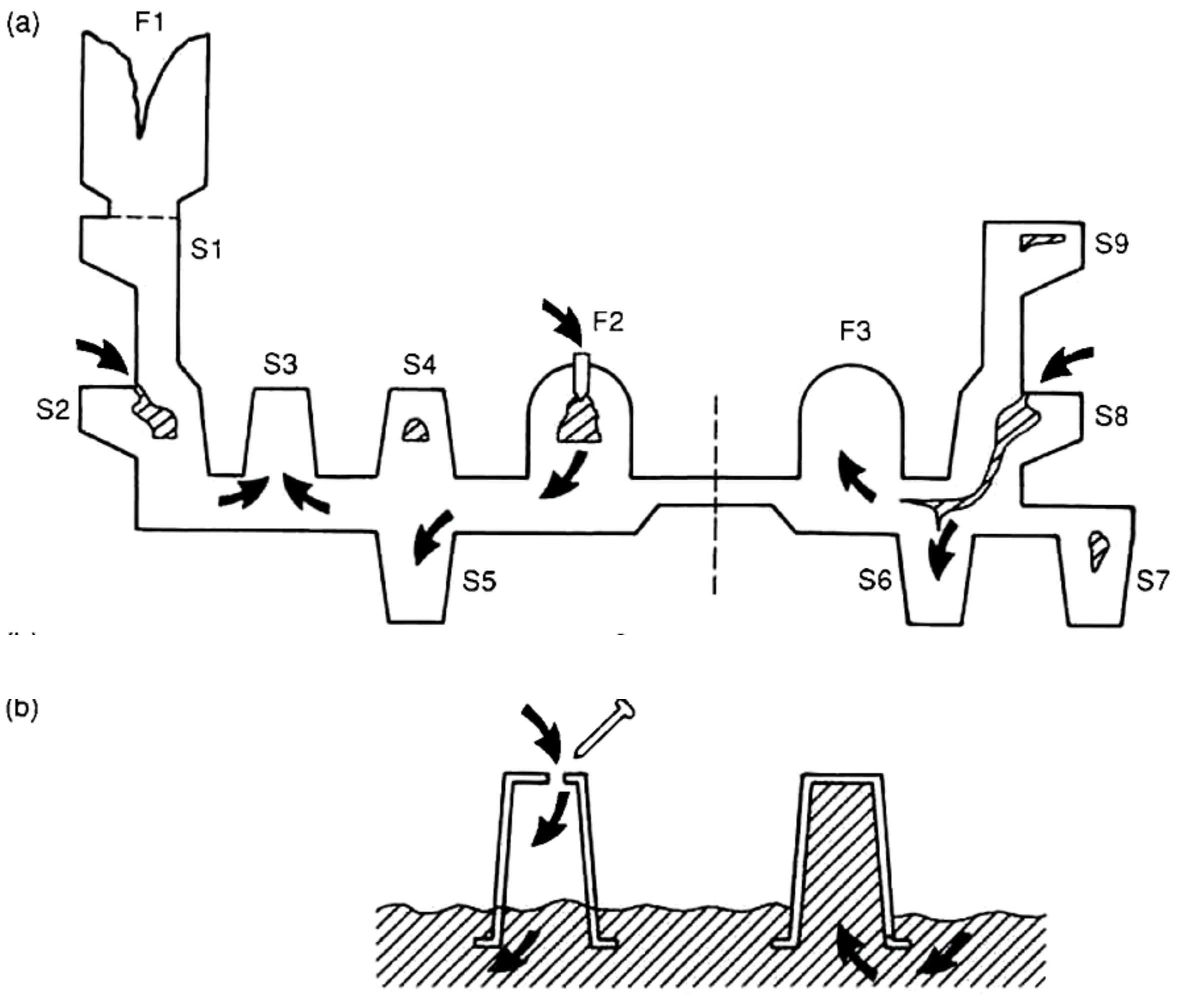
Figure 3.36 Use of indirect pad to promote feeding of heavy sections in valve body casting (after Daybell[85])

Rule 6: Pressure Gradient Requirement

"There must be sufficient pressure differential to cause the feed material to flow, and the flow needs to be in the correct direction"

- If the pressure gradient needed to cause the liquid to flow along the path is not available, then feed liquid will not flow to where it is needed.
- A positive pressure gradient from the outside to the inside of the casting will help to ensure that the feed material travels along the flow path into those parts of the casting experiencing shrinkage.
- Driving forces for liquid flow
  1. **positive pressure such as atmospheric pressure and/or the pressure due to the hydrostatic head of metal in the feeder**
  2. **reduced or even negative pressure generated within poorly fed regions of some castings**

Place feeders high to feed downhill,
place gates low to fill uphill



Variation in feeder head

F1: Open head
F2: Atmospheric head
F3: Blind head

Figure 6.10 *(a) Castings with blind feeders, F2 is correctly vented but has mixed results on sections S3 and S4. Feeder F3 is not vented and therefore does not feed at all. The unfavourable pressure gradient draws liquid from a fortuitous skin puncture in section S8. See text for further explanation. (b) The plastic coffee cup analogue: the water is held up in the upturned cup and cannot be released until air is admitted via a puncture. The liquid it contains is then immediately released.*

Blind feeders that are placed low on the casting are unreliable !

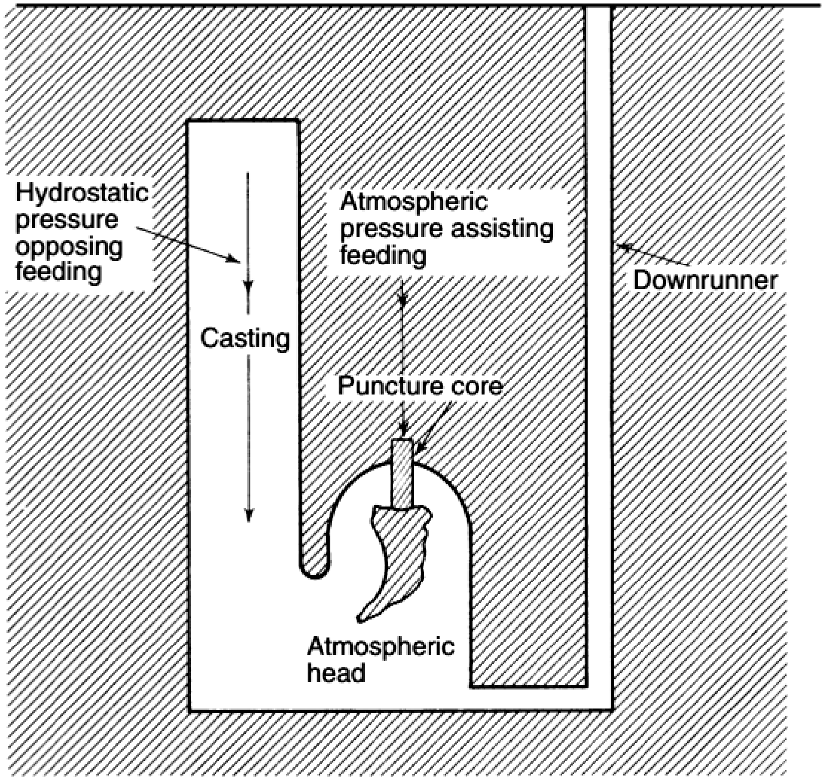


Figure 3.28 Principles of atmospheric feeder head

The pencil core or atmospheric pressure core or puncture core is made of dry sand and is positioned so that it extends from outside the mould to well inside to the heart of the feeder.

Atmospheric head can exert pressure in a closed system equivalent to

1.30 m of steel
1.15 m of copper
4.34 m of aluminium

Air pressure can still get into the feeder even after a solid skin is formed.

Effective for skin-freezing-range alloys

Begins to function only after the heavy section has been isolated from the open head

Not suitable for some nonferrous alloys, because when a partial vacuum is formed inside, the soft skin of the whole casting and feeder may collapse due to the atmospheric pressure

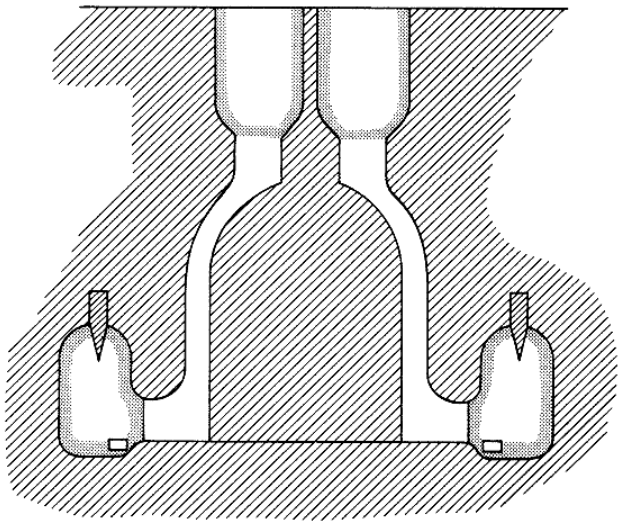


Figure 3.29 Atmospheric heads in combination with open heads

Rule 7: Pressure Requirement

"There must be sufficient pressure at all points in the casting to maintain the dimensional accuracy of the casting and to suppress the formation and growth of cavities"

- This is a hydrostatic requirement relating to the suppression of porosity

  contrasts with the previous pressure gradient requirement that relates to the hydrodynamic requirement for flow (especially flow in the correct direction!)

Analogy:

Pressure requirement for nucleating a gas bubble inside a liquid metal

$$P = P_a + h\rho g + 2\gamma/r$$

- A fall in internal pressure may cause a variety of problems:

1. Liquid may be sucked from the cast surface.
2. The internal pressure may fall just sufficiently to unfurl, but not fully open the population of bifilms.
3. The internal pressure may fall sufficiently to open bifllms so that a distribution of fine and dispersed microporosity will appear.
4. The internal shrinkage may cause macroshrinkage porosity to occur, especially if there are large bifilms present as a result of poor filling of the casting.
5. If there is insufficient opportunity to open internal defects, the external surface of the casting may sink to accommodate the internal shrinkage.

4. Shrinkage Porosity

4.1 Initiation of shrinkage porosity

- In the absence of gas, and if the feeding is adequate, then no porosity will be found in the casting.
- Many casting are sufficiently complex that one or more regions of the casting are not well fed, the internal hydrostatic tension will reach a level at which an internal pore may form.
- If solid feeding can reduce the internal tension sufficiently low so that internal porosity formation do not occur, then solidification shrinkage appears on the outside of the casting.

4.2 Growth of shrinkage porosity

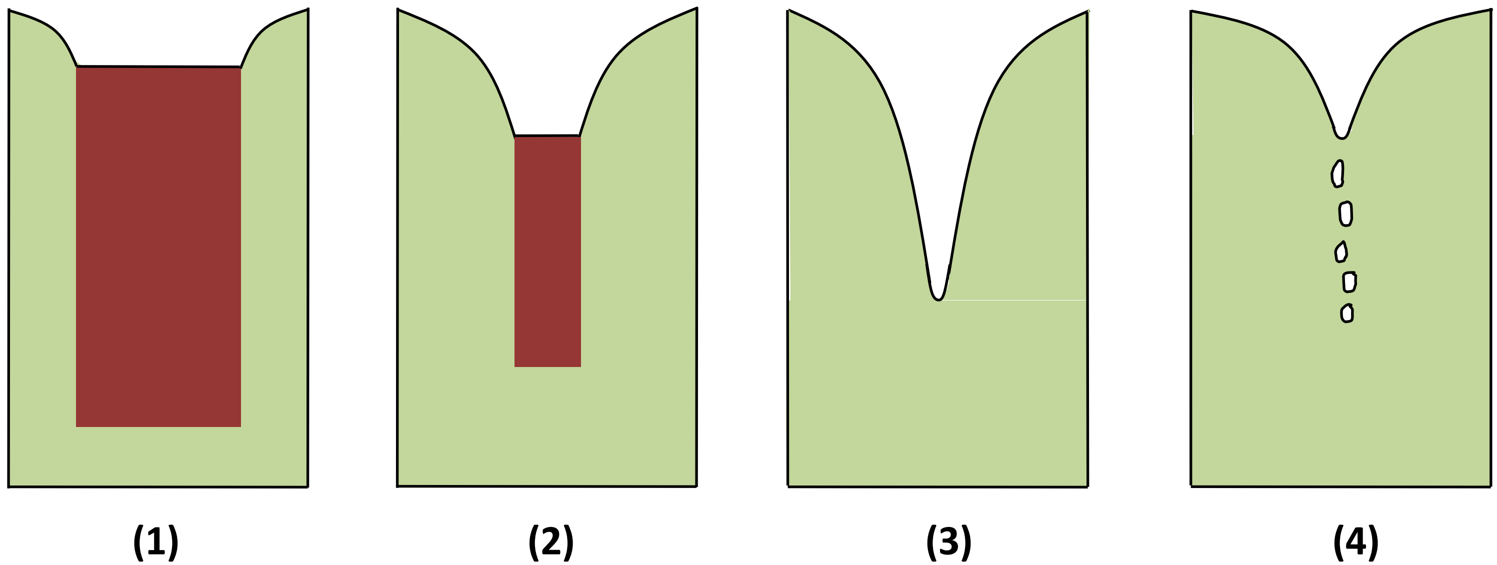
- For internal pores which are nucleated within the stressed liquid, the **initial growth is extremely fast**; in fact it is explosive !
- After this explosive growth, the subsequent growth of pores was occurs more leisurely, occurring at a rate which was controlled by the rate of solidification (or rate of heat extraction).
- For surface initiated pores, the initial stress is lower, and the puncture of the surface will occur relatively slowly as the surface collapses plastically into the forming hole.
- For shrinkage porosity which grows like a pipe from the free surface of the melt there is no initial fast growth phase at all.

  The cavity grows at all stages simply in response to the solidification shrinkage, the rate being set by the rate of heat extraction from the casting.

4.3 Final forms of shrinkage porosity

- During liquid feeding, the gradual progress of the solidification front towards the centre of the casting is accompanied by the steady fall in liquid level in the feeder.

- These linked advances by the solid and liquid fronts generate a smooth conical funnel as shown below. This is a **shrinkage pipe**.



Stages in the development of a primary shrinkage pipe. Stage (4) is the appearance of stage (3) on a planar cut section if the central pipe is not exactly straight (i.e. it is not a series of separate pores).

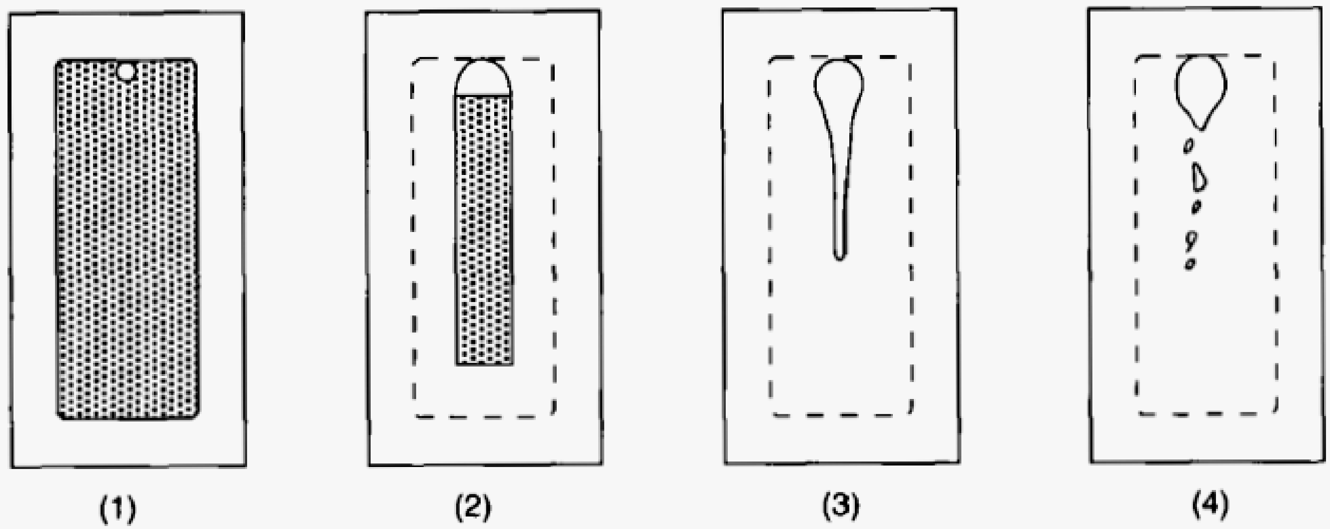
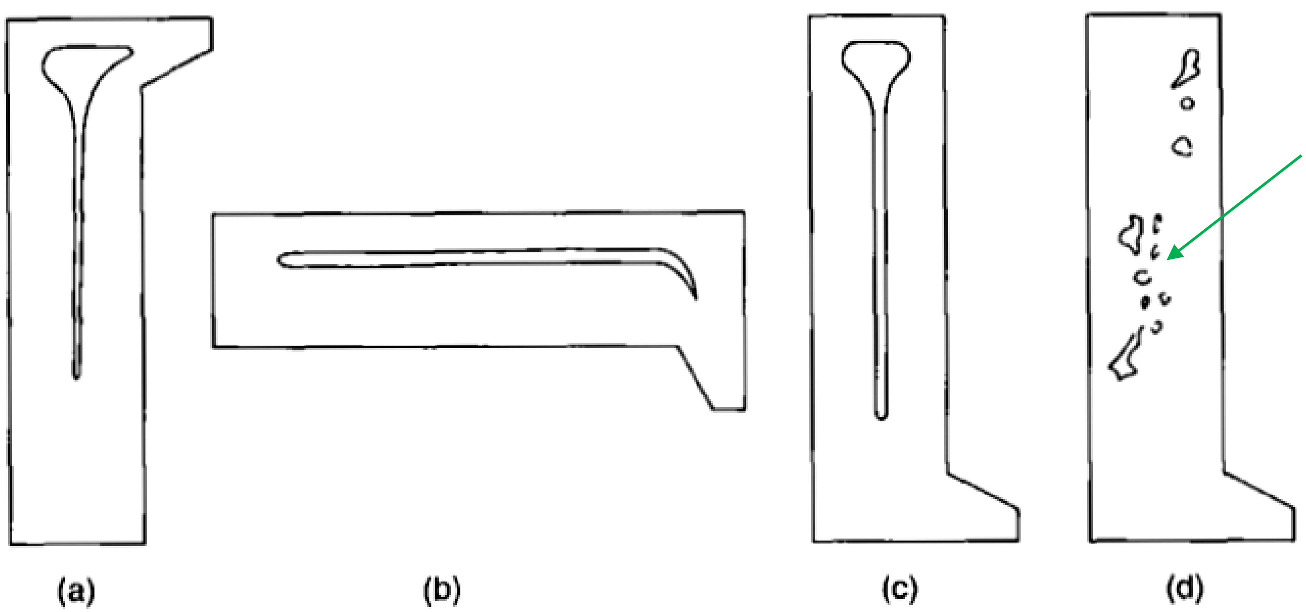


Figure 7.22 *Stages in the development of an internal shrinkage cavity. Stage (4) is again the equivalent cut section to stage (3). Note that the porosity is not concentrated in the thermal centre, but is offset from the centre of the trapped liquid region, outlined by the broken line, by gravity.*



Porosity having no relation to the casting geometry cannot be shrinkage porosity.

(perhaps the pores are air bubbles entrained during the pour)

Figure 7.23 Shrinkage cavity in a short-freezing-range alloy as a function or orientation a, b and c. Porosity shown in d illustrates some other source of porosity (it cannot be a shrinkage type because of its random form, not linked to the casting geometry).

Next Class

MME **345**, Lecture **B:08**

The Design of Feeding Systems

2. Feeding calculations