MME 345

Lecture **B:07**

The Design of Gating System

1. Fluidity of liquid metal

Ref:

1. J. Campbell, Castings, Butterworth-Heinemann, 2003
2. P. R. Beeley, Foundry Technology, Butterworth-Heinemann, 2002

Topics to discuss....

1. Introduction
2. Fluidity of liquid metals
3. Factors controlling fluidity

1. Introduction

- ☐ The pouring of molten metal into the mould is one of the critical steps in metal casting

  behaviour of the liquid and its subsequent solidification and cooling determine whether the cast shape will be properly formed, internally sound and free from defects

- ☐ The success of the pouring operation depends upon

  1. certain qualities of the metal itself, which influence liquid flow

     e.g., composition and temperature

  2. properties and design of the mould

     including the nature of the moulding material and the gating technique used to introduce the metal into the mould cavity

- ☐ Whilst the metal is in the liquid state the foundryman is also concerned with **forces acting upon the mould** and with **volume contraction** occurring during cooling to the solidification temperature

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2. Fluidity of Liquid Metals

- ☐ Having got the metal successfully through the running system,
  the question now is,

  Will it fill the mould ?

- ☐ The ability of the molten metal to continue to flow while it continues to lose temperature and even while it is starting to solidify is commonly termed as **fluidity**

- ☐ A **fluid** liquid fills through all the interstices of the mould and provides sharp outlines and faithful reproduction of design details

  inadequate fluidity may be a factor in short run castings or in poor definition of surface features

Foundryman's fluidity vs. physicist's fluidity

- Fluidity defined in physics as the reciprocal of viscosity, which is defined as the force required to move a surface of unit area at unit velocity past an equivalent parallel surface at unit distance
  - **a measure of the capacity of a liquid to transmit a dynamic stress in shear**
  - **more directly related to the capacity of a liquid to flow under its own pressure head is the kinematic viscosity, that is the absolute viscosity divided by the density**

- Under casting conditions, the requirement of liquid is, however viscous, to conform in time to the shape of its container.

- In terms of casting alloys, the fluidity is, thus, defined as the maximum distance L_f to which the metal will flow in a standard mould before solidification.

- The failure of a liquid to fill the mould cavity results not from high viscosity but from premature solidification.

  thermal conditions and mode of solidification are thus the critical factors with respect to cessation of flow. The concept of fluidity takes these aspects into account.

Maximum fluidity length vs. Continuous fluidity length

- **In a long mould, the metal will continue to flow until stopped at distance L_f by solidification.**
- **This is the maximum fluidity length (or simply the fluidity) L_f of the metal.**

- **In a short mould, the migration of the growing choke may reach the end of the channel before the channel is closed.**
- **The flowing metal will re-melt the choke completely and the flow will continue uninterrupted.**
- **This is the continuous fluidity length or the critical fluidity, L_C of the metal.**
- **Thus, for a channel equal to or smaller in length than L_C, the flowing capacity or fluidity becomes infinite.**

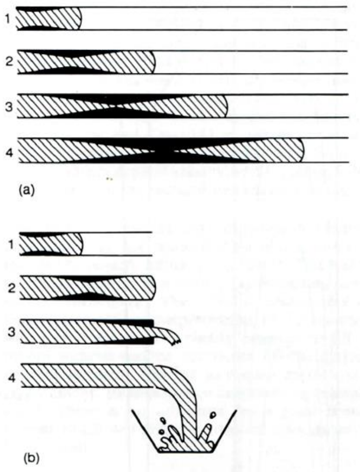


Figure 2.61 *The concepts of: (a) maximum fluidity length showing the stages of freezing leading to the arrest of flow in a long mould; and (b) the continuous flow which can occur if the length of the mould does not exceed a critical length, defined as the continuous-fluidity length.*

Measurement of fluidity

- ❑ Fluidity cannot be assessed from individual physical properties
- ❑ Empirical tests have been devised based on conditions analogous to the casting of metals in the foundry
- ❑ Measure fluidity as the maximum distance covered by molten metal in standardized systems of enclosed channels before cessation of flow

Typical Test Methods

1. Straight flow channel
2. Spiral test
3. Standardised fluidity test

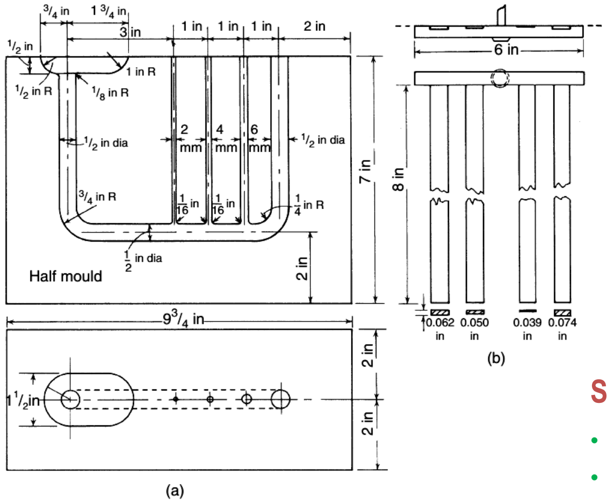


Figure 1.6 Multiple channel fluidity test castings. (a) U test (from Reference 23), (b) Strip test (from Cooksey *et al*[22]) (courtesy of Institute of British Foundrymen)

Straight flow channel

- excessive length
- sensitivity to levelling

Spiral test

Controlling parameters to obtain truly standard conditions during test:

- metal head pressure
- rate of liquid metal delivery
- thermal and surface characteristics of mould

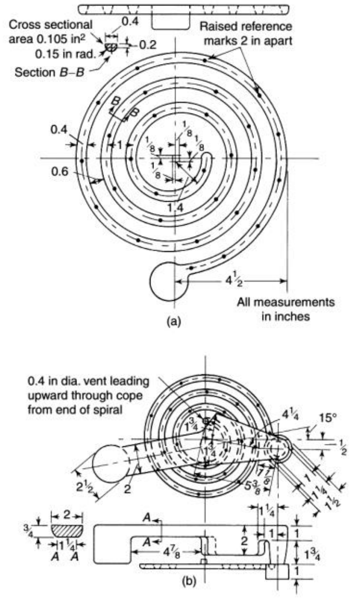


Figure 1.1 Spiral fluidity test casting. (a) Standard fluidity spiral, (b) arrangement of down-gate and pouring basin for standard fluidity spiral (courtesy of American Foundrymen's Society)

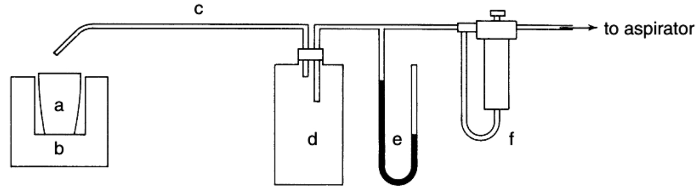


Figure 1.2 Vacuum fluidity test apparatus (from Ragone *et al*[10]). (a) Crucible of metal; (b) electric resistance furnace; (c) fluidity test channel; (d) pressure reservoir; (e) manometer; (f) cartesian manostat (courtesy of American Foundrymen's Society)

❑ This method is the closest approach to complete standardisation.

❑ These refinements of technique approach the ideal of excluding mould variables and measuring fluidity as a property of the metal alone.

3. Factors Controlling Fluidity

1. Composition and mode of solidification
   - **Long- and short-freezing-range alloys**
2. Liquid velocity
3. Solidification time
   - **Modulus**
   - **Heat transfer coefficient**
   - **Superheat**
   - **Latent heat**
   - **Mould temperature**
4. Surface tension

3.1 Composition and Mode of Solidification

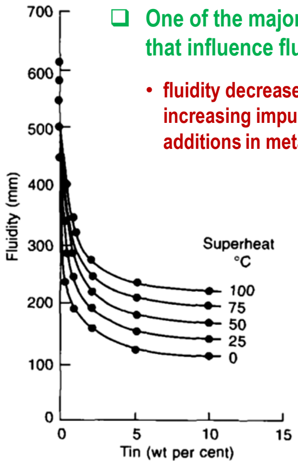
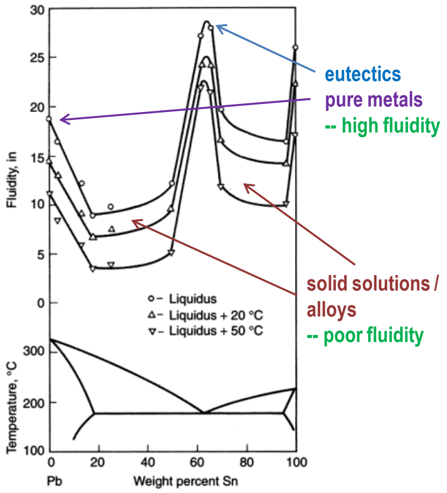


Figure 3.4 *Variation of fluidity with composition of Al–Sn alloys. Data from Feliu et al. (1960).*

- ☐ **One of the major factor that influence fluidity**
  - **fluidity decreases with increasing impurity/alloy additions in metal**



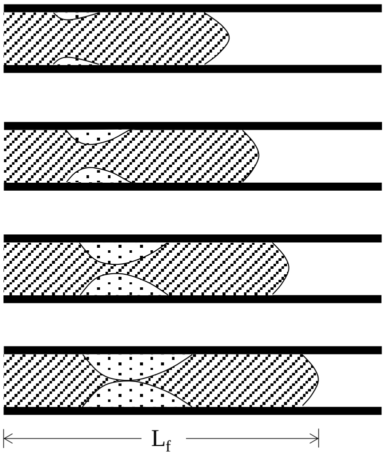
eutectics
pure metals
-- high fluidity

solid solutions / alloys
-- poor fluidity

Figure 1.4 Relationship between composition and fluidity of lead–tin alloys

Why does eutectic/pure metal has higher fluidity than solid solution/alloy?

Short/skin freezing range alloys

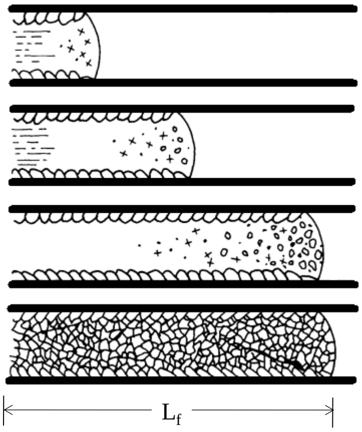


- Solidifies at a single or narrow-range of temperature
- Planar front of solidification
- Solidification starts from the mould wall and grows inside
- The point of solidification migrates downstream
- Solidification needs to be 100 % complete at one location for flow to stop
- Total fluidity length for these materials:

$$L_f = V\,t_f$$

V = velocity of flow (assuming constant !!)
t_f = time for solidification

Long freezing range alloys



- Freezes over a wide range of temperatures
- Dendritic mode of solidification
- The liquid metal transforms into a slurry of dendritic crystals and starts to offer resistance to the flow of liquid metal
- At some point of solidification (in the range of 20 – 50 % solid), the flow ceases.
- Total fluidity length for these materials:

$$L_f = x\,V\,t_f$$

x = fraction of solids in melt when solidification ceases, which depends somewhat on metal head pressure

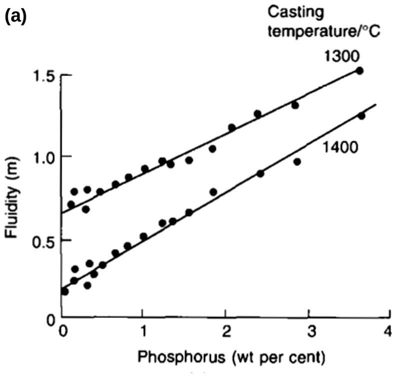
Having the same mode of solidification,

why do eutectics have higher fluidity than the pure metals?

☐ This may be understandable in terms of the sum of two effects:

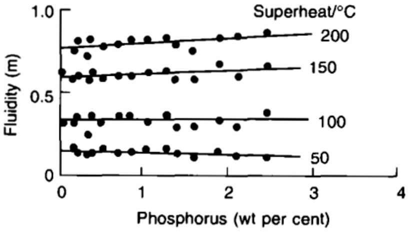
1. **Pure metals used for experiments are not always that pure, while the fluidity of eutectic of exact composition was not measured.**
2. **The pure metals may be exhibiting some dendritic growth, due to the presence of impurity.**
3. **The determination of fluidity of alloy at a constant temperature automatically increases the fluidity of the eutectic because of its low melting point.**

(a)



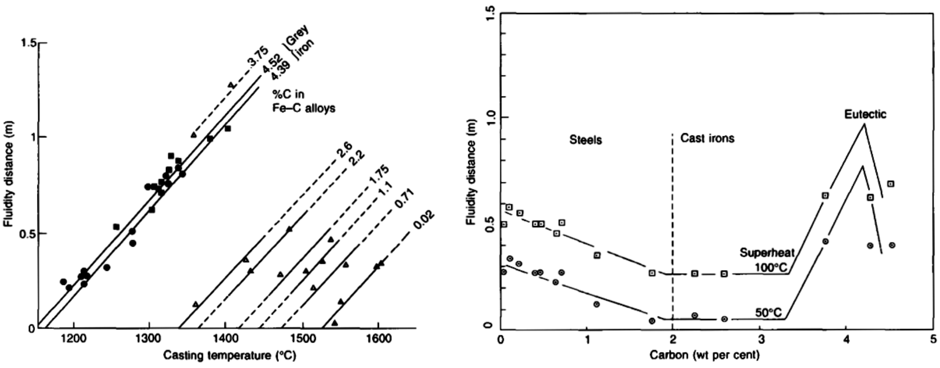
An increase in the fluidity of cast iron due to the addition of phosphorous is well-known.

(b)



But when plotted as a function of superheat (the casting temperature minus the liquidus), the phosphorus addition hardly affects the fluidity.

This indicates that, the powerful effect of phosphorus on cast iron is solely the result of its action to reduce its freezing point.



(a)

(b)

(a) Effect of temperature on the fluidity of Fe-C alloys
(b) The same data plotted as a function of composition

Fluidity and castability

- The improved fluidity of short versus long freezing range materials forms the basis of much foundry technology.

Cast iron vs. Steels

cast irons, being eutectic or near-eutectic alloys, have excellent fluidity have enormous uses over cast steel

Al-Cu alloys vs. Al-Si alloys

the poor fluidity of Al-Cu alloys is one of many reasons for which this once vastly used alloy becomes almost extinct

3.2 Liquid Velocity

- The velocity is explicit in the equations for fluidity

  Thus, fluidity increases linearly with increase in velocity.

  However, increasing fluidity by increasing liquid velocity is a mistake.

- Attempt to improve filling with a maximum speed usually fail to produce good casting because of the complicating effects of bulk and surface turbulence.

- Thus, in general, up to small head heights of the order of 100 mm fluidity can be raised linearly with increase in speed of flow.

  However, further increases in speed appear to be counterproductive if castings relatively free from defects are required.

3.3 Solidification Time

- From the definition of fluidity, it is clear that the greater the solidification time, $\mathbf{t_f}$, the further the metal will run before freezing.

  Increasing solidification time is a far more satisfactory way to improve the filling of castings than increasing the velocity, since the surface turbulence problems can therefore be kept under control.

Sand Mould :

$$t_f = \frac{\pi}{4\, K_m \rho_m C_m} \left\{ \frac{S\, \rho_s\, L}{T_m - T_o} \right\}^2$$

Metal Mould :

$$t_f = \frac{\rho_s\, L\, S}{h\,(T_m - T_o)}$$

L – latent heat
h – heat transfer coeff
ρ_s = density of solid
S = section thickness of solid
$K_m\ \rho_m\ C_m$ = head diffusivity of mould

- Variables affecting solidification time are: **m, L, h, T_m, T_o**

Modulus, m

- ☐ As solidification time is influenced by the casting thickness or shape (Chvorinov's rule), the fluidity of liquid is also affected by the modulus of casting.

Chvorinov's rule

k, k' = mould constants, m = modulus
h = heat transfer coeff., V = velocity of liquid

Sand mould: $t_f = k\ m^2$

Chill mould and thin-walled sand casting: $t_f = k'\ m / h$

Sand moulds: $L_f / m = kVm$
Metal moulds: $L_f / m = k'V / h$

L_f = fluidity, V = velocity

These are the two powerful formulae to assist in the prediction of whether a mould will fill.

- **L_f/m for metal mould is constant in a given mould**
- **For sand mould, fluidity varies with the square of the casting section**
- **For 4-mm section Al-casting in sand mould, $L_f / d \approx 100$,**
  ➔ A 4-mm section casting should run 400 mm before solidifies

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Hear transfer coefficient, h

- ☐ A reduction in the rate of heat transfer will benefit fluidity
- ☐ For this reason **insulating ceramic coatings** are applied to all gravity and low-pressure dies
- ☐ For sand moulds, **acetylene black** is applied from a sooty flame giving very substantial increases in fluidity, by a factor of 2 or 3.

  this dramatic improvement in fluidity is used in some precision sand foundries, allowing thin-walled castings to be filled that could not otherwise be cast

Superheat

☐ Increases in casting temperature benefit fluidity in a direct way

fluidity increases linearly with the superheat
(defined here as the excess of casting temperature over liquidus temperature)

Why do eutectics have higher fluidity?

☐ At constant superheat the fluidity of the eutectic is almost exactly that expected from the rule of mixtures

a rule of mixtures would have predicted the fluidity of the pure elements and the eutectic to lie on a straight line

☐ When determined at a constant temperature, however, the eutectic has the advantage of a large effective superheat, and the fluidity of the eutectic is correspondingly enhanced, becoming significantly higher than that of either of the pure metals

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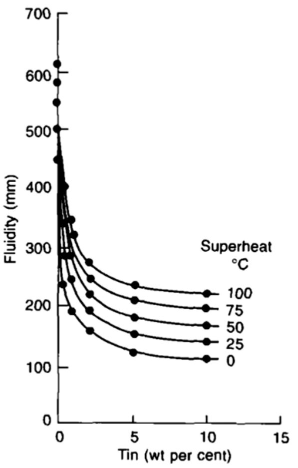


Figure 3.4 *Variation of fluidity with composition of Al–Sn alloys. Data from Feliu et al. (1960).*

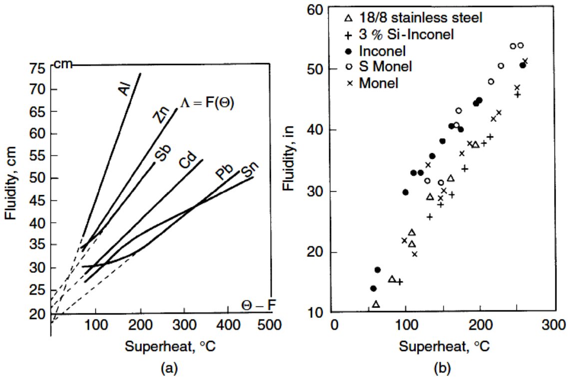


Figure 1.3 Influence of superheat on fluidity: (a) pure metals (from Portevin and Bastien[11]) (courtesy of Institute of Metals) (b) alloys (from Wood and Gregg[12]) (courtesy of Institute of British Foundrymen)

Superheat ↑ ➔ fluidity ↑

Latent heat, L

- The latent heat given up on solidification will take time to diffuse away, thereby delaying solidification, and extending fluidity

  the good fluidity of the hypereutectic Al-Si alloys is attributed to the fact that pure Si has a latent heat of solidification 4.65 times greater than that of Al

$$t_f = \frac{\pi}{4\, K_m \rho_m C_m} \left\{ \frac{S\, \rho_s\, L}{T_m - T_o} \right\}^2$$

- Changing from pure Al to pure Si, the comparative freezing time

$$\frac{t_{Si}}{t_{Al}} = \left\{ \frac{T_{Al} - T_0}{T_{Si} - T_0} \right\}^2 \left\{ \frac{\rho_{Si}}{\rho_{Al}} \right\}^2 \left\{ \frac{L_{Si}}{L_{Al}} \right\}^2$$

$$= (0.460)^2 \times (0.867)^2 \times (4.65)^2 = 3.4$$

So solidification time (and hence fluidity) for pure Si is 3.4 times greater than that of pure Al

Mould temperature, T_0

- For most casting processes mould temperature is fixed at or close to room temperature
  - **for such processes, there is little or nothing that can be done to mould temperature to affect fluidity**

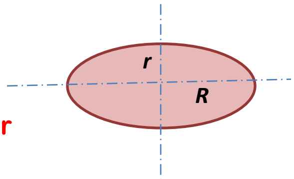
- The intermediate temperatures of gravity and high-pressure dies, usually at around 300 to 400 C, do contribute modestly to the increase of fluidity in these casting processes
  - **die temperatures are sometimes raised a little to gain a little extra filling capability**

- However, for investment casting the ceramic shell allows a complete range of temperatures to be chosen without difficulty
  - **when the mould temperature is raised to the melting point of the alloy, the fluidity becomes infinite; i.e. the melt will run for ever!**
  - **example: thin-walled Al-alloy investment casting (600 C); Ni-based single crystal for turbine blade (1450 C)**

3.4 Surface Tension

- ❑ The back pressure experienced by the liquid metal due to surface tension, P_{ST}, resisting entry into a narrow mould

$$P_{ST} = \gamma \left\{ (1/r) + (1/R) \right\}$$



For cylindrical mould (r = R), $P_{ST} = 2\gamma/r$

For thin, wide mould (R = ∞), $P_{ST} = \gamma/r$

- ❑ This back pressure must be overcome by the metal head pressure $h\rho g$, otherwise the liquid will not enter the section

- ❑ In larger round or square sections, where the radii R and r both become large, in the range of 10 to 20 mm, the effects of surface tension become sufficiently small to be neglected for most purposes. Large sections are, therefore, filled easily.

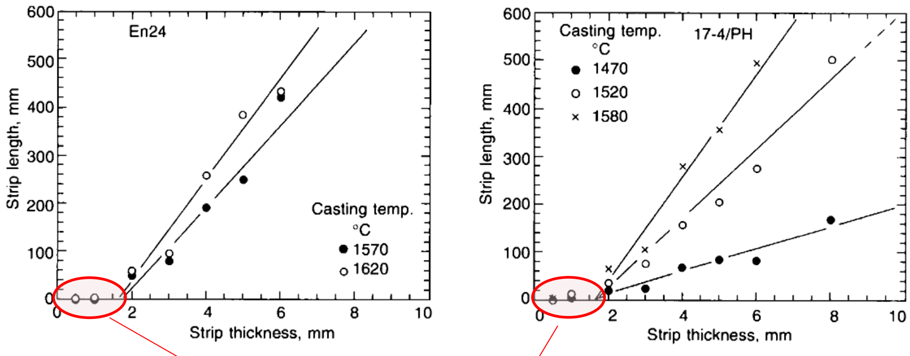


Figure 3.14 *(a) Fluidity data for a low alloy steel, and (b) for a stainless steel poured in a straight channel, furan-bonded sand mould (Boutorabi et al. 1990).*

Fluidity zero for narrow moulds!

To summarize:

How to control fluidity for a particular alloy?

Anything that increases t_f will increase fluidity.

1. High pouring temperature (increase superheat)
2. Reduction rate of heat transfer
3. Application of ceramic/graphite coating
4. Increase modulus and velocity of flow

Next Class

MME **345**, Lecture **B:13**

The Design of Gating System

2. Introduction to the gating system