TALAT Lecture 3205

The Fluidity of Molten Metals

19 pages, 17 figures

Advanced Level

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Objectives:

– To introduce the concept of fluidity of molten metal and its influence on the production of castings
– The student will understand the relevance of fluidity, the means by which this is measured and the effect of alloy type.

Prerequisites:

– Basic understanding of foundry processes.
– Knowledge of phase diagrams.
– Basic physics and mathematics.

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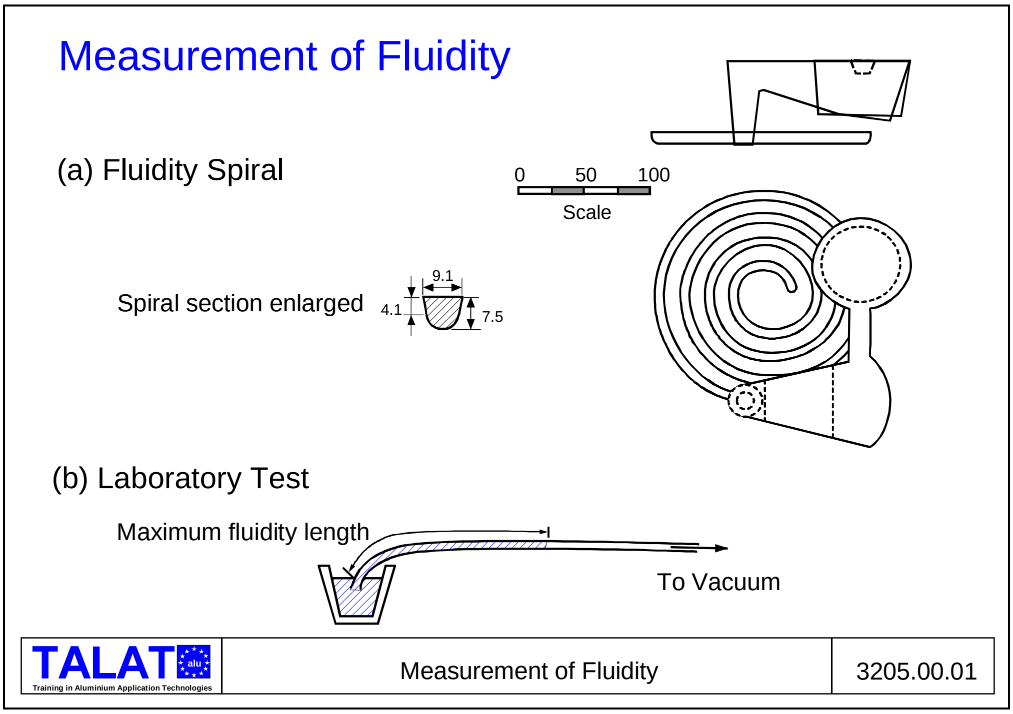
Introduction

Fluidity is, in casting terminology, the distance to which a metal, when cast at a given temperature, will flow in a given test mould before it is stopped by solidification. Fluidity is therefore a length, usually measured in millimetres or metres.

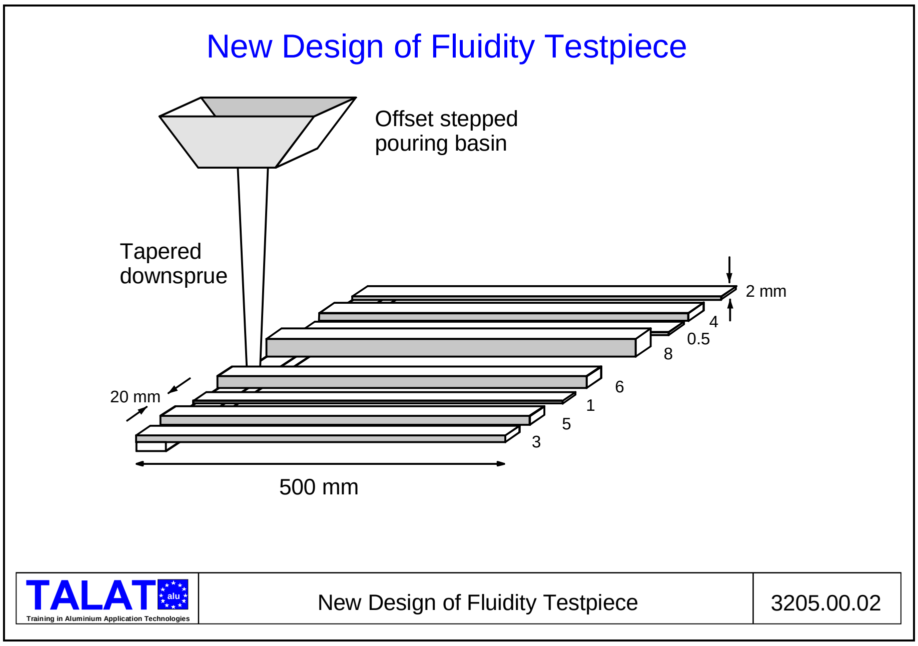
(It is not to be confused with the physicists' definition as the reciprocal of viscosity.)

Measurements of Fluidity

Traditionally fluidity has been measured in a spiral mould. The rationale behind this is clearly the desire to compress the fluidity test into as small a mould as possible, and that the flow distance is sensitive to levelling errors, and that these are minimised by the spiral path of the liquid (**Figure 3205.00.01**).



A large number of variations of the spiral test have been used over the last half century. Although widely used, they are also widely criticised for a number of reasons, probably the most important of which is that the test bears no clear relation to its application in real castings. For instance, if it is found that a particular alloy at a reasonable casting temperature gives a spiral fluidity length of 500 mm, how does this relate to a particular casting which might be bottom gated and with a wall 350 mm high and 4 mm thick. Will the casting fill or not? Will it be prevented from filling by premature freezing? These are questions which have not been answered up till now. However, they are capable of being answered even from the results of the spiral test as we shall see.



However, the questions are probably more easily and directly answered by more recent, simpler designs of test which have been developed over recent years at The University of Birmingham, UK. **Figure 3205.00.02** shows the latest variant in which a series of long strips of different thickness is filled simultaneously from a common runner bar. One mould provides a plot of fluidity as a function of thickness and several moulds poured at different temperatures completely characterises the fluidity of a given material. Some results from this will be shown later.

Solidification Rates

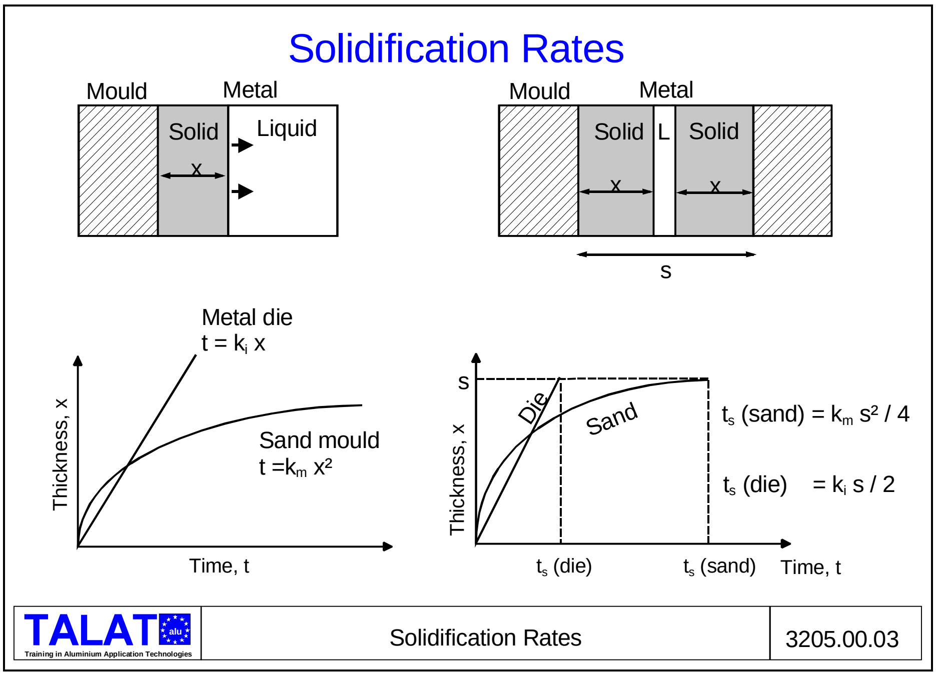


Figure 3205.00.03: As a necessary piece of background, we need to know that the time *t* for the solidified metal to reach a thickness x in a sand mould, where the rate of loss of heat from the casting is controlled by the poor conductivity of the mould, is given by the parabolic law of thickening:

$$t \;=\; km\, x^2 \qquad \text{(1a)}$$

In the case of a die, the heat flow away from the casting is fast through the casting and die, since both are metals, but is now limited by heat flow across the metal/die interface, especially as the air gap opens up as the casting contracts away from the die. The equivalent relation in this case is a linear law for the rate of thickening:

$$t \;=\; k_i\, x \qquad \text{(1b)}$$

where

– k is a constant,

- and the subscript m indicates heat transfer controlled by the mould (i.e. the mould is a poor conductor of heat)
- and the subscript i heat transfer controlled by the metal/mould interface (which is generally applied to most types of aluminium alloy die casting operations, including gravity, low pressure and high pressure die casting).

Thus the time for complete solidification, t_s, of a sand casting of section thickness S (= twice the maximum value of x)

$$t_s = \frac{k_m \cdot S^2}{4} \qquad (2a)$$

and an equivalent die casting

$$t_s = \frac{k_i \cdot S}{2} \qquad (2b)$$

Short Freezing Range Alloys

We will now consider the fluidity of *short freezing range* metals and alloys (**Figure 3205.00.04**). This shows the mode of solidification from the outside walls in towards the centre as the metal proceeds along the mould. A point to notice is the remelting of the part of the frozen solid nearest the source of hot metal. For this reason the solidified zone migrates progressively along the mould, trailing behind the liquid tip. However, the important point to be noted is that the flow of metal is stopped when the two freezing fronts meet (although this point is some distance back from the flow tip). This corresponds to 100 % solidification at this point.

We can therefore write down a formula for fluidity in terms of the solidification time t_S, the velocity of flow V, and the fluidity distance L_f. Assuming that V is approximately constant, we have simply

$$L_f = V \cdot t_S \qquad (3)$$

and hence from equations 2a and 3 we have for sand moulds

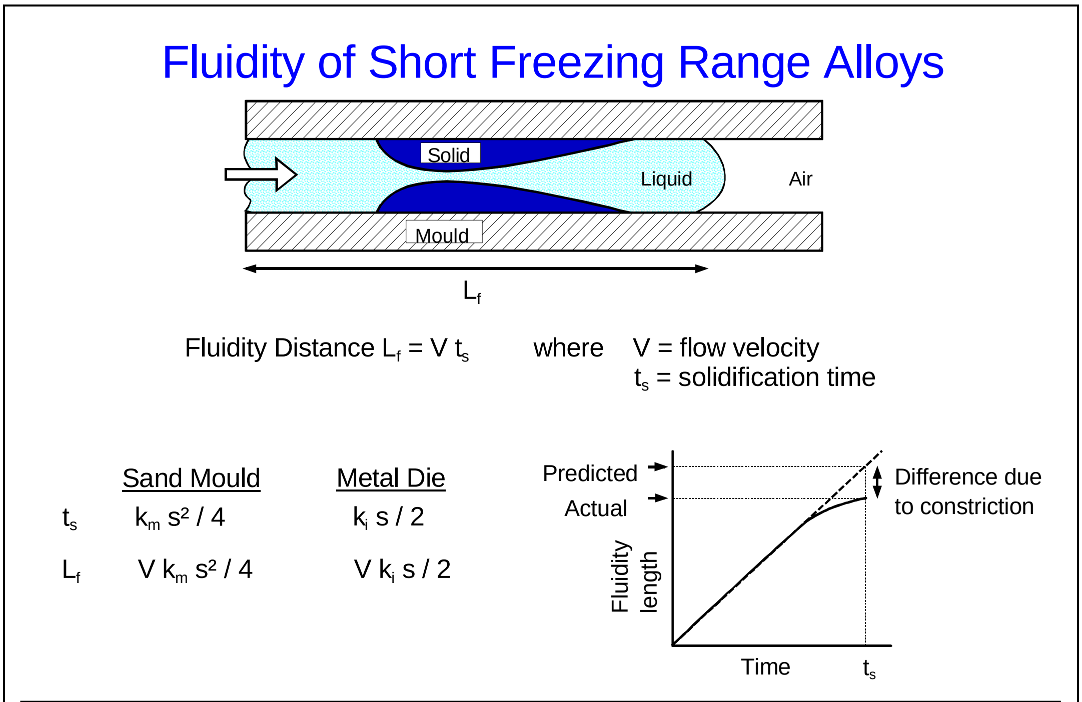
$$L_f = \frac{V \cdot k_m \cdot S^2}{4} \qquad (4a)$$

and for dies:

$$L_f = \frac{V \cdot k_i \cdot S}{2} \qquad (4b)$$

These formulae overestimate the fluidity length somewhat because V is not completely constant; the melt does slow a little as the constriction due to freezing starts to take hold.

However, this is a relatively minor effect, and the formula is in fact quite a useful approximation.



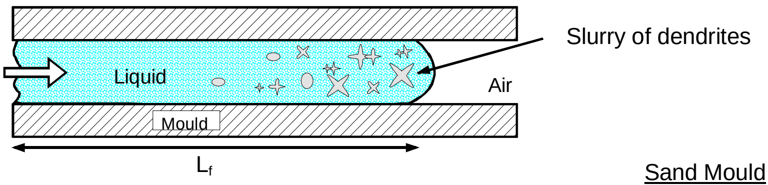
Fluidity of Short Freezing Range Alloys 3205.00.04

Long Freezing Range Alloys

We will now move onto the fluidity of *long freezing range* alloys. The solidification of such alloys in a rapidly flowing stream is somewhat different (**Figure 3205.00.05**).

The solidification front is now, of course, no longer planar but dendritic, and because freezing is occurring in a moving liquid, the bulk turbulence in the liquid causes turbulent eddies to sweep through the dendrites, carrying pockets of hot liquid into these cooler regions, and thus remelting dendrite arms and other fragments, to build up a slurry of dendrite debris. As heat is lost from the slurry, the slurry thickens, gradually becoming so thick that it is too viscous to flow. This occurs at different fractions of solid in different alloys, and also seems to be influenced by the metallostatic head driving the flow. In general, however, the flow of liquid is arrested when the volume fraction of solid is somewhere between 25 and 50 %.

Fluidity of Long Freezing Range Alloys



Flow stops when 25 - 50% solid is present, i.e. when x = S/8 to S/4

	Sand Mould	Metal Die
	$t = k_m x^2$	$t = k_i x$
25% solid	$t = k_m S^2 / 64$	$t = k_i S / 8$
50% solid	$t = k_m S^2 / 16$	$t = k_i S / 4$
Therefore	$L_f = V k_m S^2 / 64$ to $V k_m S^2 / 16$	$V k_i S / 8$ to $V k_i S^2 / 4$
Remember that for short freezing range alloys:	$L_f = V k_m S^2 / 4$	$V k_i S / 2$
Therefore $\frac{\text{Short freezing range}}{\text{long freezing range}}$:	4 - 16	2 - 4

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If we now rewrite equation 1 allowing for the fact that only 25 to 50 % freezing is required to arrest flow, then $x = S/4$ to $S/8$, and from equation 1 we obtain therefore $t = k_m S^2 / 16$ to $t = k_m S^2 / 64$, so that

$$L_f = \frac{V \cdot k_m \; S^2}{16} \quad to \quad \frac{V \cdot k_m \cdot S^2}{64} \tag{5}$$

By comparison with equation 4a, it is immediately clear that fluidity is expected to fall by a factor of 4 to 16 in long freezing range alloys when cast in sand moulds. This is often seen in practice.

For dies, a similar approach gives

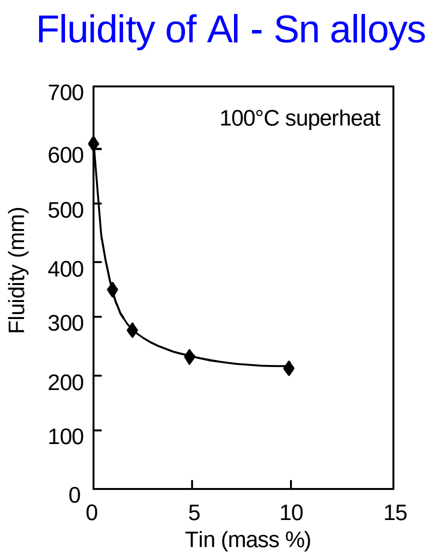
$$L_f = \frac{V \cdot k_i \cdot S}{4} \quad to \quad \frac{V \cdot k_i \cdot S}{8} \tag{6}$$

By comparison with equation 4b, this shows that the fluidity falls by a factor of only 2 to 4 when long freezing range alloys are cast in dies.

Effect of Impurities

Sometimes, however, the large predicted fall for sand castings is not seen. In practice the fall appears to be only perhaps a factor of 2. In such cases it is likely that the so called pure metal components of the alloy are in fact not so pure; even slight impurities

will greatly reduce the fluidity of pure elements, thus easily accounting for the fact that further alloying appears to reduce the fluidity further by only the factor of 2.
This effect is illustrated by the results (**Figure 3205.00.06**) which show the effect of small concentrations of tin on the fluidity of pure aluminium.

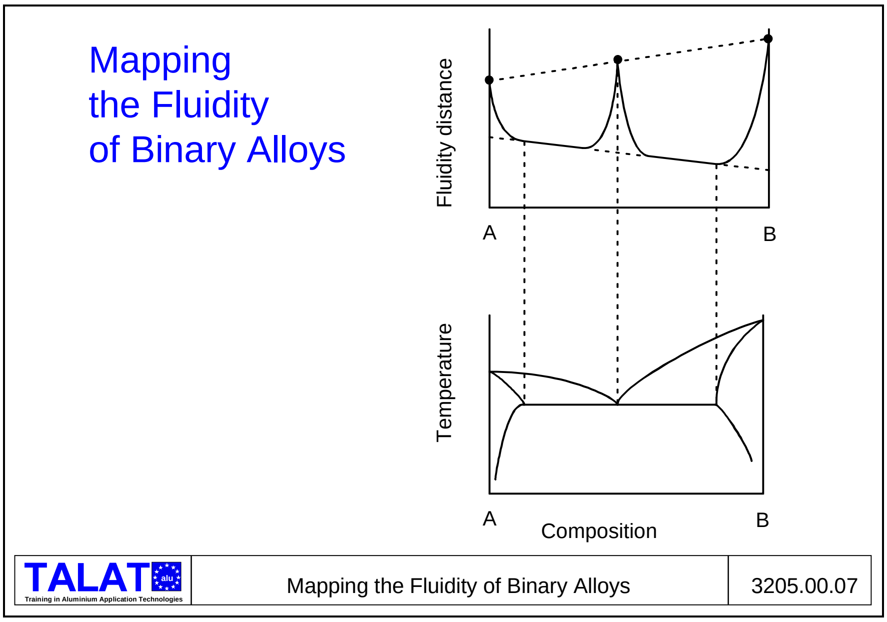


TALAT Fluidity of Al - Sn Alloys 3205.00.06

Map of Fluidity

We can now create a useful map of the performance of a complete series of binary alloys in terms of their ability to flow before being arrested by solidification (**Figure 3205.00.07**).

The map can be created in stages as follows: firstly the pure metal components and the eutectic are skin-freezing materials (all solidifying at a single temperature) and so have high fluidities. These three points should lie on a single line, but the extreme sensitivity of fluidity to even minor impurities often will seriously affect the height of these cusps. Also, of course, the cusps are so high and narrow that it is easily possible in practice to miss the peak when attempting to locate it experimentally.



The regions in between the three peaks have fluidities which are lower by a factor of 2 to 16, but more typically by a factor of 2 to 4. This factor can be different at the two ends, of course. Furthermore, we may probably assume a method of mixtures type argument between these extremes, which gives a straight line connection. The map is then complete, as shown here.

Figure 3205.00.08: In practice the Al-Si system turns out to be a surprise when the peak in fluidity is not at the equilibrium eutectic around 11% Si, but is nearer 15% Si. This corresponds of course to the non-equilibrium eutectic composition. It is expected that the presence of Na or Sr as promoters of the eutectic phase, and suppressers of the primary Si, might influence the position and height of the fluidity peak somewhat. The general increase in fluidity with increasing silicon content in this particular alloy is the result of the powerful effect of Si. Its latent heat of solidification is among the highest of all natural elements, and is nearly 5 times greater than that of Al. Thus t_S is significantly increased as Si levels are raised.

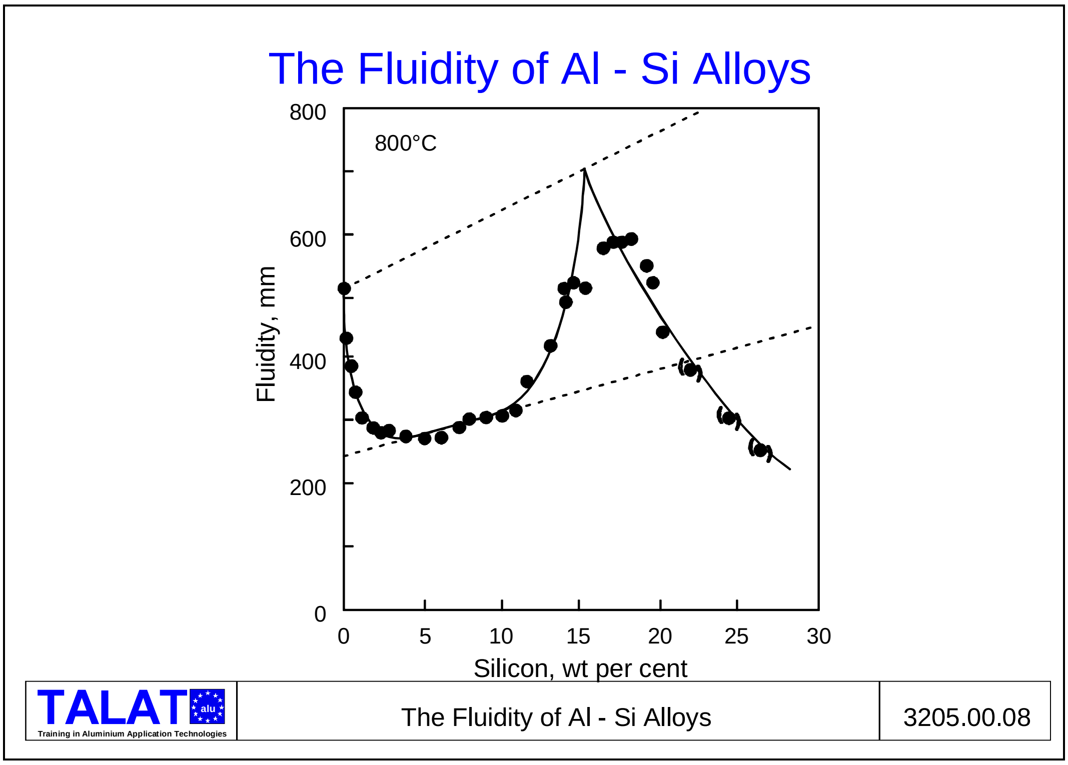
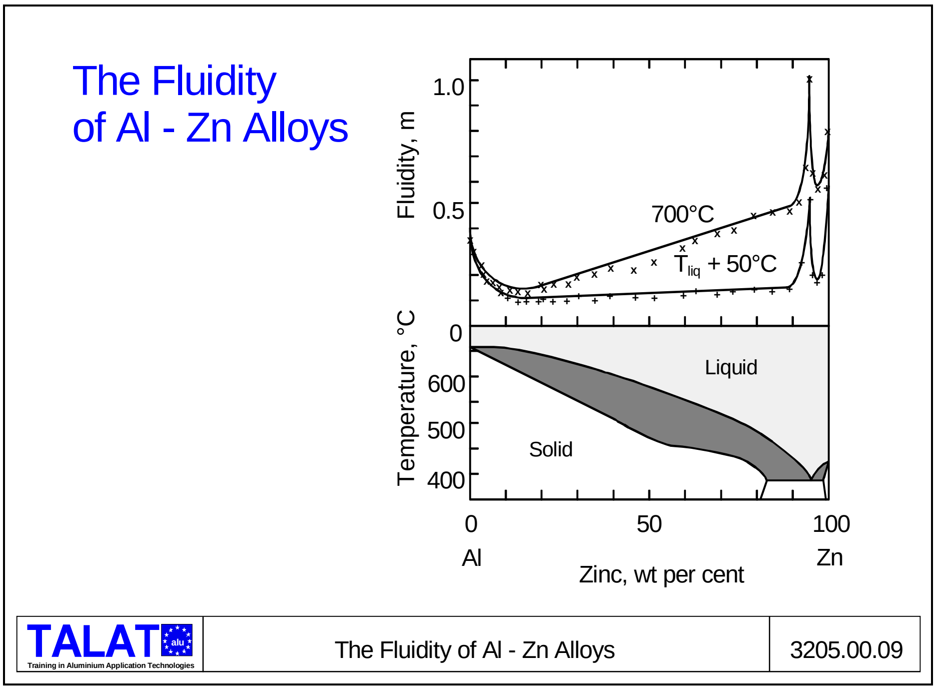
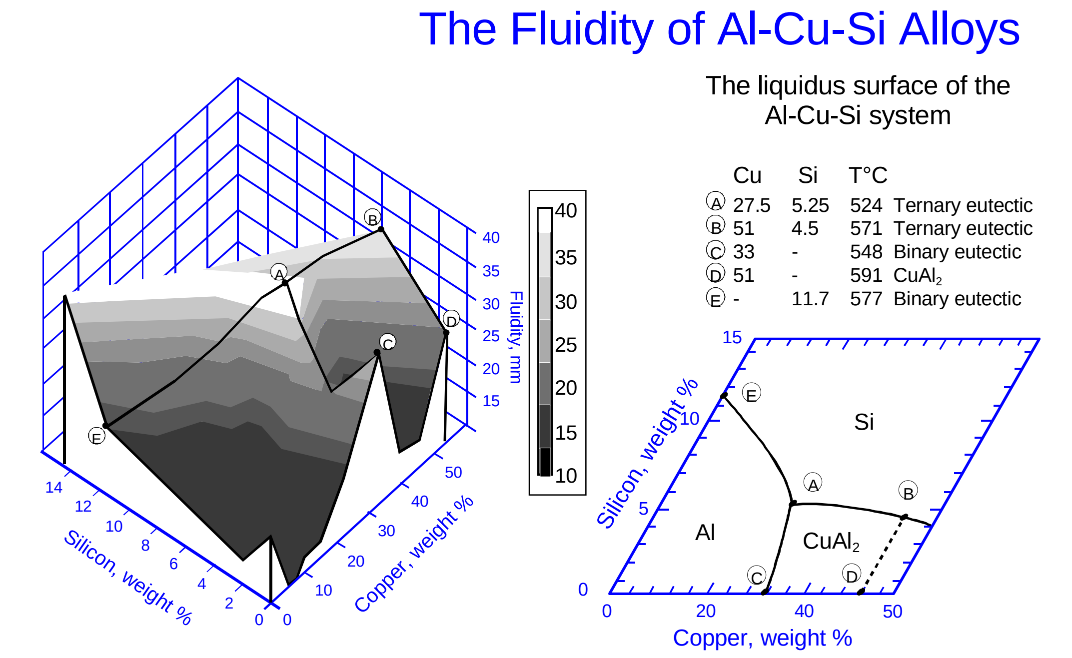


Figure 3205.00.09 shows results for Al - Zn alloys and again confirms that fluidity is highest for pure metals and at the eutectic composition. This is true whether a constant pouring temperature (700° C) or constant superheat (liquidus temperature plus 50° C) is used.



For more complicated systems, the fluidity map becomes even more complicated as seen in this three dimensional plot for Al - Si - Cu alloys (**Figure 3205.00.10)**. These experimental data show that the maximum fluidity coincides with the ternary eutectic 'A'. When designing new foundry alloys it should be mandatory to create such a map. The sensitivity or robustness of the fluidity of a new material would then be clear from the start, or slight modifications might result in a much improved optimisation of the castability of the material without significant loss of other properties. In the past the importance of this critical parameter has been sadly overlooked.



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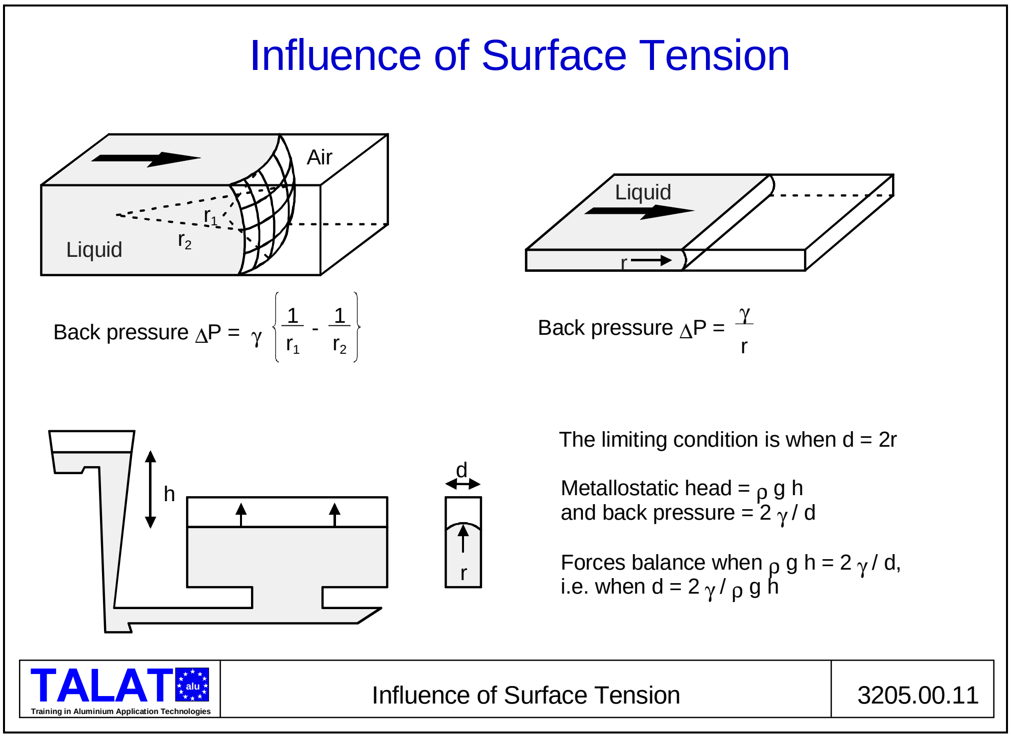
Effect of Surface Tension

In addition to the effect of solidification on limiting the distance to which metals will flow in moulds and dies, the effect of surface tension becomes important in thin sections i.e. less than 5 mm or so (**Figure 3205.00.11**).



The effect of surface tension can be likened to a back pressure, often known as capillary repulsion - repulsion since moulds and dies are designed to avoid wetting by the liquid metal; if the mould or die was wetted then the effect would be the familiar phenomenon of capillary attraction, as water climbing a glass capillary tube. The formula which allows the effect to be quantified is

$$\Delta P = \gamma \left\{ \frac{1}{r_1} - \frac{1}{r_2} \right\}$$

where ΔP is the pressure difference across the curved interface, γ is the surface tension of the liquid metal, and r_1 and r_2 are the two radii at right angles which define the curvature of the liquid meniscus. In the filling of a wide plate we may consider that one of the radii becomes nearly infinity, so that if the remaining radius is now r, the expression reduces to

$$\Delta P = \frac{\gamma}{r}$$

Thus the pressure exerted by the meniscus to prevent a thin section from filling is inversely proportional to the section thickness. If we equate this to the pressure available due to the metallostatic head $\rho g h$, where

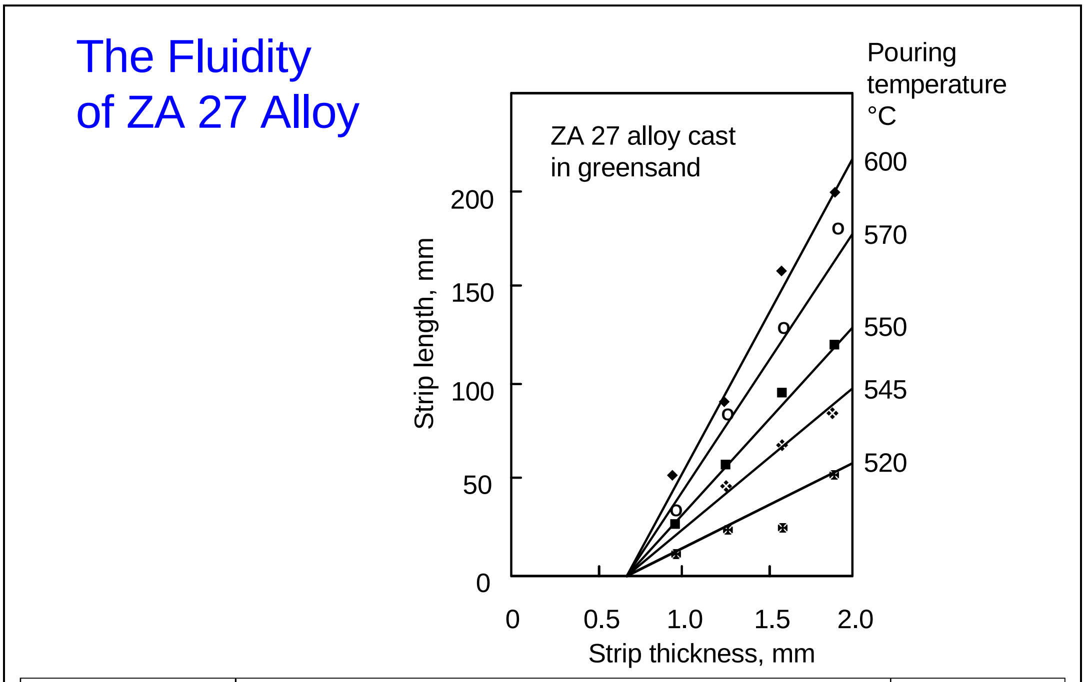
ρ is the density of the liquid,
g the acceleration due to gravity, and
h the metallostatic head,

then we can calculate the section thickness d = 2r which just will not fill. This is

$$d = \frac{2 \cdot \gamma}{\rho \cdot g \cdot h} \qquad (7)$$

Effect of Section Thickness

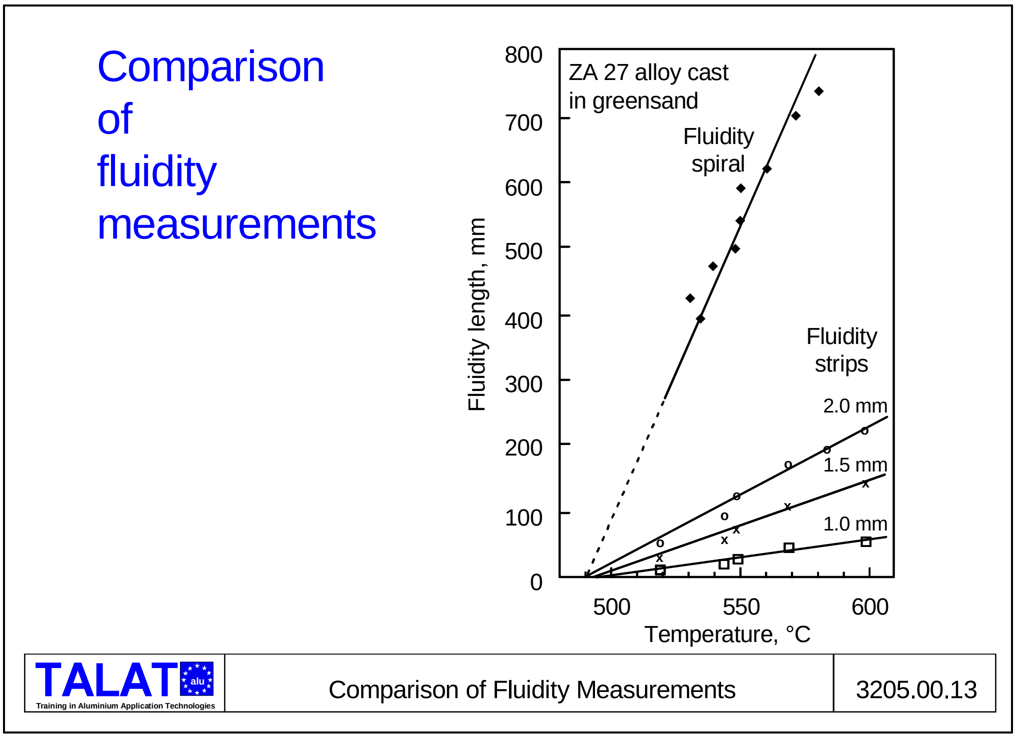
Figure 3205.00.12 shows the effect of casting a series of strips of different thickness at a variety of temperatures. Clearly they all extrapolate backwards to a critical thickness 0.63 mm which just will not fill (i.e. has zero fluidity distance under all conditions of pouring temperature) for this height of mould. For the Zn - 27 % Al alloy we can work out from Equation (7) the effective surface tension. When this exercise is carried out for most aluminium alloys the result is approximately 1.5 - 2.0 N/m. Since γ for liquid aluminium and its alloys is actually nearer 0.9 - 1 N/m, we can conclude that the presence of the strong and tenacious aluminium oxide film approximately doubles the effect of the natural surface tension of the liquid in preventing the liquid from entering narrow sections.



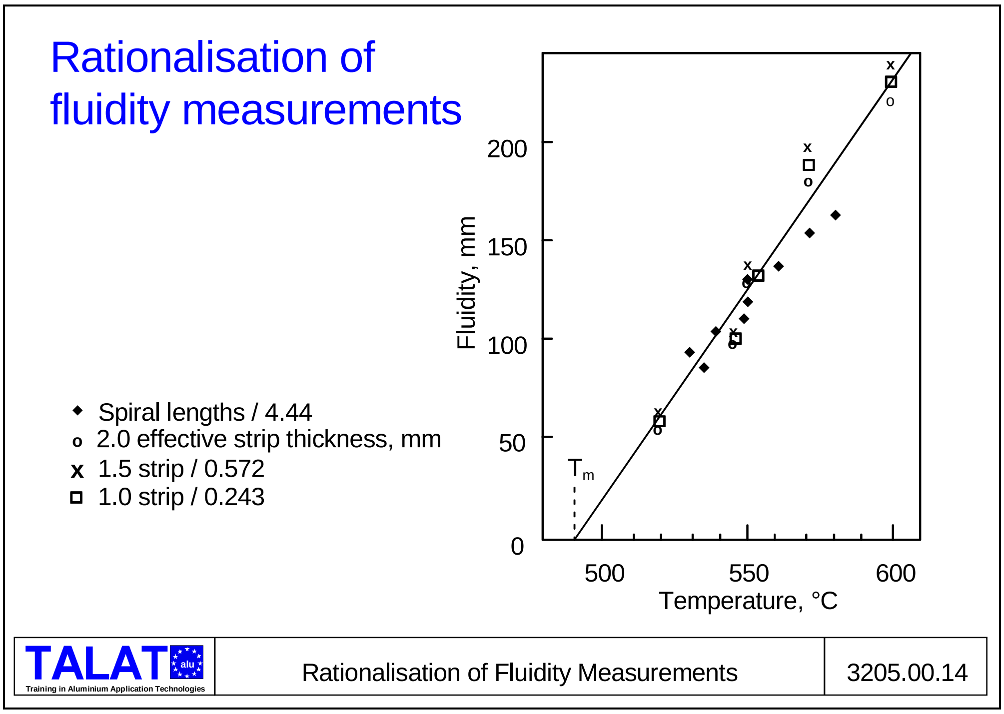
TALAT	The Fluidity of ZA 27 Alloy	3205.00.12

The determination of fluidity as a function of thickness of section in this way is a valuable method of determining the effective surface tension in filling problems. The technique is recommended for more general use.

Figure 3205.00.13 shows more fluidity data for this alloy cast in sand moulds, illustrating the considerably greater distance to which the metal will run in the wide section of a fluidity spiral, as opposed to the narrow plate-like sections.



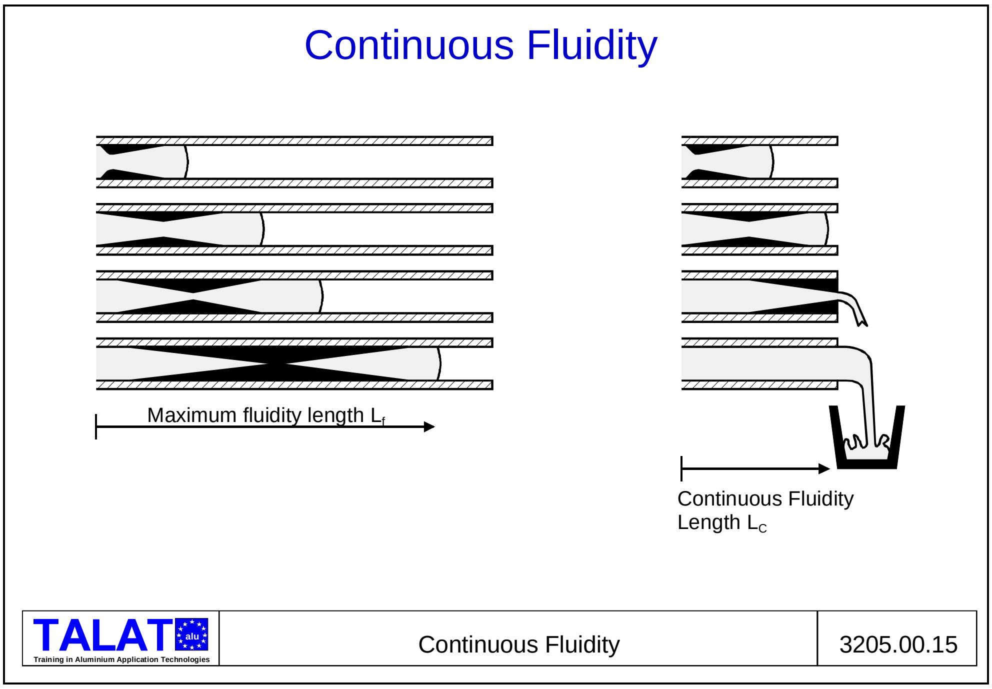
However, **Figure 3205.00.14** shows how all these results become equivalent when allowance is made for the effect of surface tension and the effect of the different cooling rates due to the difference in geometric modulus; all the results condense together onto a single curve when reduced to the effective fluidity in a 2 mm plate section. This result emphasises the fact that all the fluidity tests give equivalent information providing allowance is made for the effects of the section on cooling rate and the effective loss of pressure head due to surface tension.



Concept of Continuous Fluidity

I would now like to introduce the concept of continuous fluidity. So far we have discussed only the maximum distance that an alloy will run in a mould. In some instances it is useful to be able to define the distance to which a metal can flow in a channel, in which the metal will continue to run for ever, at least in principle.

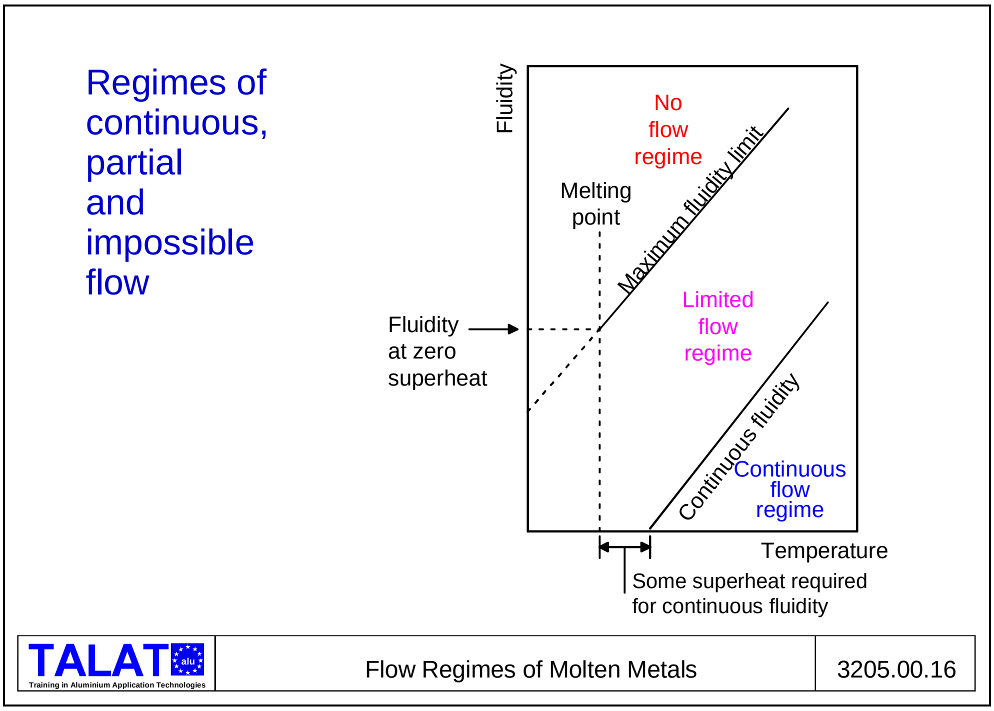
This can happen in short lengths of channel where the channel opens out subsequently into a larger section. It occurs because the arrival of new hot metal in the channel continuously remelts the originally solidified material, effectively redepositing this further down the channel. The effect is seen in **Figure 3205.00.15**.



With the movement of the solidifying plug progressing down the channel, if the channel opens out into a larger section before the plug finally closes, then the plug will completely remelt, effectively being pushed out of the channel. Thus the subsequent flow will be unchecked by solidification - the channel will remain completely open while hot metal continues to flow.

This effect is valuable in running systems, where the section thickness is small, but the system remains open because of the remelting effect. Interestingly, the continuous fluidity concept can allow the casting engineer to predict how small a running system section he can use, and what corresponding casting temperature will be required to avoid premature freezing in the running system, resulting in a short-run casting.

Figure 3205.00.16 illustrates how continuous fluidity contrasts with normal (i.e. maximum) fluidity. Maximum fluidity still exists at zero superheat because there is latent heat in the liquid which will allow the metal to continue to flow for a short time. For continuous fluidity, some superheat is always required for the remelting action to occur. The various regimes of continuous, partial, and impossible flow to make castings are worth remembering.



Very little experimental work has been performed on continuous fluidity. More deserves to be carried out on this important and useful concept.

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).

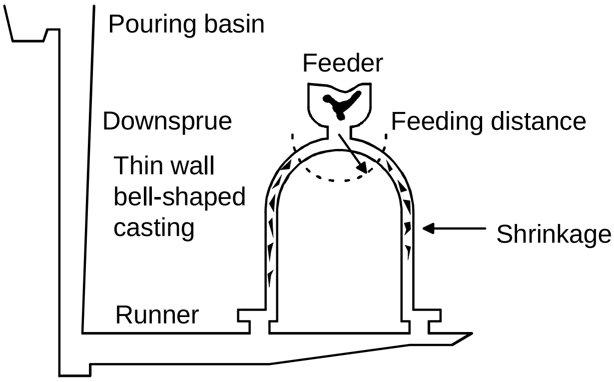
The imprecise situation for aluminium alloys contrasts with the precise and well known condition in simple carbon-manganese steels of section thickness upwards of 15 mm cast in green sand moulds. Here the feeding distance is easily demonstrated to be a maximum of 2.5 times the section thickness away 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

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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),

or

- 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 for 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.

Literature

Campbell, J.: Castings, Butterworth Heinemann, 1991

List of Figures