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FILLING SIMULATION OF TILT CASTING

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Reliable fluidity data for commercial aluminium foundry alloys are not readily available. However, such data are important in the optimization of mould filling calculations. The term fluidity in the foundry is used to indicate the distance of a molten metal can flow in a mould of a constant cross-sectional area before it solidifies. This definition is different from the definition presented in physics which describes fluidity as the inverse of viscosity, a fundamental temperature related property of a liquid.

Fluidity is mainly a complex technological property and it depends upon many factors which can be categorized as follows:

1. Metal variables: chemical composition, solidification range, viscosity, heat of fusion.
2. Mould and mould/metal variables: heat transfer coefficient, mould and metal thermal conductivity, mould and metal mass density, specific heat, surface tension.
3. Pouring method variables: gravity casting, tilt casting, low pressure die casting, high pressure die casting.

By carefully selecting the appropriate combination of these variables, fluidity can be controlled. This plays a key role for thin walled castings because misruns, often encountered in these castings, are a result of insufficient fluidity of the liquid metal. It is not easy to control fluidity due to the large number of variables involved. However, if variations in fluidity due to uncontrolled factors can be estimated, defect problems, such as unexpected misruns and/or cold shuts, can be overcome and process costs reduced.

Keywords: gravity casting, tilt casting, computer simulation

1. THEORETICAL BACKGROUND

1.1. Solidification of alloys

Unlike pure metals and eutectics, the flow of alloys ceases at the leading tip of the flowing stream. As the solute concentration is increased, the mode of solidification changes from growth of columnar grains with more or less planar front (for pure metals and dilute alloys) to the formation of equiaxed dendrites or columnar dendrites where the dendrite arms fracture forming equiaxed grains (for solute rich alloys). These grains flow downstream with the liquid metal, until a critical fraction solid is reached and the flow stops by choking at the tip of the freezing metal as shown in *Figure 1* [1–3].

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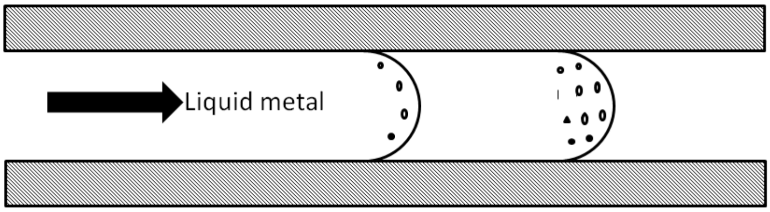

Figure 1
Schematic representation of solidification in alloys

Flemings developed simplified mathematical models for the fluid length of metals that are poured into a cylindrical channel in a mould [2, 5]. For the fluidity of alloys:

$$L_f = \frac{A\rho v (f_s^{cr} H + C\Delta T)}{Sh(T - T_{cr})}\left(1 + \frac{B}{2}\right) \quad (1)$$

where:

L_f	[mm]	fluid length
A	[mm^2]	mould surface area
ρ	[kgm^{-3}]	density
v	[mms^{-1}]	velocity of metal flow
f_s^{cr}	[%]	critical fraction solid
H	[$kJkg^{-1}$]	heat of fusion
C	[$kJkg^{-1}K^{-1}$]	specific heat
ΔT	[K]	temperature interval
S	[mm]	circumference of the mould channel
h	[$Wm^{-2}K^{-1}$]	heat transfer coefficient
T	[K]	temperature of the alloy
Tc	[K]	coherency temperature
h	[$Wm^{-2}K^{-1}$]	heat transfer coefficient
α	[m^2s^{-1}]	thermal diffusivity of mould
Δy	[mm]	choking range
K	[$Wm^{-1}K^{-1}$]	thermal conductivity

$$B = \frac{h\sqrt{\pi\alpha\Delta y}}{K\sqrt{v}}$$

The method greatly simplifies the fluid-flow problem by neglecting friction and acceleration effects. Flemings' model is based on the assumptions that:

– the solid particles form during the flow in the fluidity channel and travel downstream with the liquid;
– the flow stops when the fraction solid near the flow tip reaches a certain value (critical fraction solid, f_s^{cr});
– the flow velocity is constant until the flow stops.

1.2. Numerical modelling of fluidity

Fluid flow pays an important role for the production of sound castings. Mould filling is the first step of every casting process. For many castings, mould filling determines the quality of the final product. Excessive turbulence, air or gas entrapment, premature solidification, form erosion, any of these factors can spoil the final product. After the mould filling phase, during solidification of castings fluid flow comes again into play. Buoyancy effects, segregation of alloy components, feeding flow are the examples of fluid flow phenomena that can take place during the solidification. Modelling of fluid flow is required if the mentioned phenomena need to be taken into account.

In order to be able to model filling properly, the following equations must be in general b solved:

- The three momentum equations (momentum conservation) together with a suitable constitutive law relating stresses and velocities, typically incompressible, Newtonian fluid for metals.
- The continuity equation (mass conservation).
- The energy equation (energy conservation).

Important phenomena that should be taken into account are e.g. temperature dependent viscosity and the tracking of free surfaces. These non-linear phenomena are often taken into account in an explicit manner in the numerical formulation which means that very small steps should be taken [4].

1.3. Effect of different parameters on fluidity

Composition is one of the main factors influencing fluidity. Small alloying additions to pure metals reduce fluidity and the fluidity of unalloyed aluminium is reduced with decreasing purity. The fluidity of aluminium-silicon alloys increases with increasing silicon content reaching a maximum at 17–18wt% silicon. The fluidity of aluminium-silicon alloys has a maximum at a silicon content well above the eutectic composition. After this maximum in fluidity, further additions of silicon will reduce the fluidity due to the increase in number of proeutectic silicon particles interfering with the metal flow. Hence, maximum fluidity will be achieved at a silicon content where the increased interference of proeutectic silicon compensates for the increased heat of fusion from the formation of silicon. [3]

Chemical composition plays an important role on castability because it influences casting properties and defects, e.g. hot tearing. The solidification range strongly influences the mode of solidification and it has been shown that the mode of solidification significantly affects the fluidity of the melt. Fluidity length is inversely proportional to the solidification interval of the alloy, i.e. mushy alloys which solidify with a large solidification range have lower fluidity than alloys which solidify with a short freezing range. [2, 3]

Superheat, i.e. the difference between the casting temperature and the liquidus temperature, is also a key factor influencing fluidity. The fluidity increases with increasing superheat for a given alloy composition. The increase in melt temperature by 1 ºC, in the temperature interval 700–760 ºC, increased the fluidity length by 1%. A linear relationship between pouring temperature and fluidity was shown for all investigated alloys. Increasing the pouring temperature, and hence the melt superheat, delays the nucleation and growth of fine grains at the tip of the flowing metal in the test channel, hence the fluidity length increases.

Fluidity also depends on the pressure height which forces the liquid metal through the pipe that forms during solidification in a narrow channel. Thus, one may expect that the taller the sprue the greater the fluidity. However, unnecessarily long sprues and special pouring cups can be avoided, which will result increased sand yield and reduced costs.

Viscosity of molten metals is quite low. Studies have shown that changes in viscosity with temperature and/or slight changes in composition are not great enough to account for the observed variation in fluidity. [6]

Ratio of fluid phase has a significant effect on the viscosity of the melt:

- Under 10% of solid phase ratio: Newtonian liquid.
- Between 10-20% of solid phase ratio: non-Newtonian liquid with relative viscosity.
-

$$\eta_r = (1 - 2{,}5\varphi)^{-1}\eta_0 \tag{2}$$

- Between 20-40% of solid phase ratio: non-Newtonian liquid with modified relative viscosity:
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$$\eta_{r_{mod}} = (1 - 2{,}5\varphi - a\varphi^2 + b\varphi^3)^{-1}\eta_0 \tag{3}$$

- Over 40% of solid phase ratio: no filling.

where:

η_0	[10^{-5} m^2s^{-1}]	Viscosity of the Newtonian liquid
φ	[%]	Ratio of the solid phase
a, b	[-]	Constants

2. Simulation of the tilt casting process

The method of simulation can be seen on *Figure 2*.

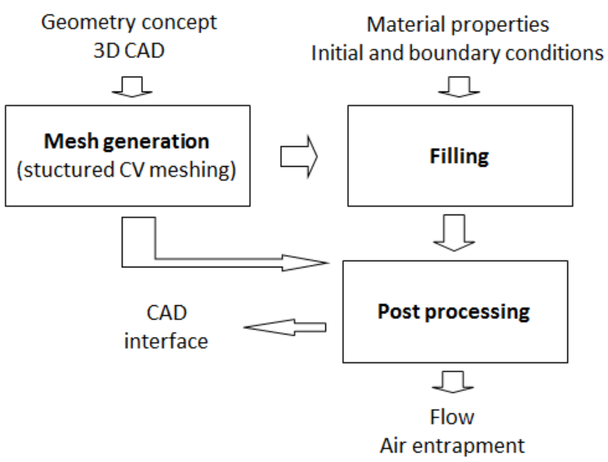

Figure 2
Method of simulation

The filling process is the point in manufacture when most of the defects are introduced into the cast part. Tilt casting solutions for gravity pouring could be described as damage limitation exercises. Here a Control Volume model is used to simulate the tilt casting process of an aluminium casting. The target of the experiments were to identify the critical process parameters and build a simulation protocol by the help of several tilt casting processes and geometries can be modelled and examined. Main factors of tilt casting are:

- If tilt casting is initiated from a tilt orientation at or below, the horizontal, during the priming of the runner the liquid metal accelerates downhill at a rate out of the control of the operator. The metal runs as a narrow jet, forming a persistent oxide flow tube. In addition, the velocity of the liquid at the far end of the runner is almost certain to exceed the critical condition for surface turbulence. Once the mold is initially inclined by more than 10° below the horizontal at the initiation of flow, it is no longer possible to produce reliable castings by the tilt casting process.
- Tilt casting operations benefit from using a sufficiently positive starting angle that the melt advances into an upward sloping runner. In this way its advance is stable and controlled. This mode of filling is characterized by horizontal liquid metal transfer, promoting a mold filling condition free from surface turbulence.
- Tilt filling is preferably slow at the early stages of filling to avoid the high velocities at the far end of the running system. However, after the running system is primed, speeding up the rate of rotation of the mould greatly helps to prevent any consequential non-filling of the castings. [7]

Technological steps of tilt casting process can be seen on *Figure 3*.

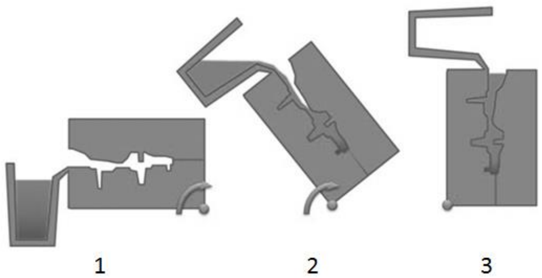

Figure 3
Technological steps of the process

1. Pouring all the required melt to the pouring ladle by controlling the following parameters:
   Gating point position of the melt to the ladle (X, Y, Z coordinates), diameter of the entering metal stream (mm), angle of the entering metal stream (°), pressure height of the melt (mm), velocity of pouring (kg/s), friction factor (%), amount of poured alloy (kg).
2. Achieving the tilt movement by controlling the following parameters:
   Downtime after filling (s), filling stop criteria (kg), initial position of the geometry (CAD), direction of rotation, centre point of rotation (X, Y, Z coordinates), axis of rotation (X, Y, Z), time of tilt (s), tilt angle (°).

3. Solidification calculation by controlling the following parameters:
   Material properties (chemical composition, latent heat, percolation threshold, nucleation ratio, phase diagram, heat conduction, specific heat, density, viscosity, heat transfer coefficient), pouring temperature, temperature values (cope, drag, core, environment), time of removal.

In the simulation constant and variable parameters were altered to achieve total cavity filling. A standard aluminium alloy was poured into a permanent metal die made of alloyed steel. The cores were produced with cold-box technology on 200 °C application tempe-rature. The environment was air on 30 °C temperature. During filling the diameter of the liquid alloy stream was 80 mm and the tilt angle was 55°. Variable parameters can be seen in the experimental model and in *Figure 4*.

Table 1
Experimental model

Number	**Melt**	**Drag & Cope**	**Drag tower**	**Cope tower**	**Pressure height**	**Pouring velocity**	**Poured metal**	**Time of tilt**	**Venting**
	Temperature								
	°C	°C	°C	°C	mm	kg/s	kg	s	
1	730	400	320	400	2	1.6	2	5	No
2	730	400	320	400	5	2.55	1.5	5	No
3	730	400	320	400	5	3.33	2.8	3	No
4	730	400	320	400	4	2.98	2.3	3	No
5	730	400	320	400	4	2.98	2.3	4	No
6	730	400	320	320	4	2.98	2.3	4	No
7	750	450	420	420	4	2.34	2.37	4.5	Yes
8	750	450	450	450	4	2.98	2.37	4.5	Yes
9	750	450	420	420	4	2.98	2.37	3	Yes

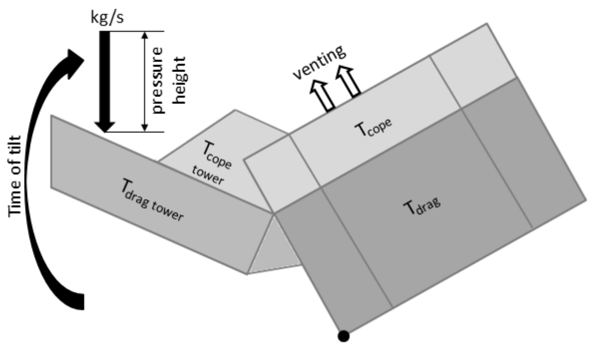

Figure 4
Variable parameters

2.1. Post-processing

- In Experiment 1–2. not enough metal was poured to the pouring ladle. The pouring velocity was too low so the melt freezes in the gating system. The entire casting cavity is unfilled. Pouring velocity and the quantity of the melt were increased to avoid freezing.
- In Experiment 3. the enlarged melt quantity helps to fill the cavity but unfilled areas detected in the lower- and upper part of the geometry. Pressure height, pouring velocity and the quantity of melt were changed to reach better filling of the cavity.
- In Experiment 4–6. the time of tilt was changed and it is determined that without venting the geometry cannot be filled completely.
- In Experiment 7–9. venting is defined to ensure the filling of the cavity. Venting is accomplished in the area of the riser head. The temperature of the die elements were increased to keep warm the melt and to avoid cold flow. The amount of the poured metal was increased till the technology limit and the time of tilt was determined correspondently to the measurements.

Using the determined technological parameters the complete cavity is filled without turbulences. Both critical parts of the cavity can be filled without significant air entrapment. Venting is effective, the geometry of the venting channel is adequate and the position of venting is applicable.

In *Figure 5* dash line represents the cavity and the dark areas shows the amount of entrapped air in the cavity. Target is achieved while all air entrapment managed to eliminate from the cavity.

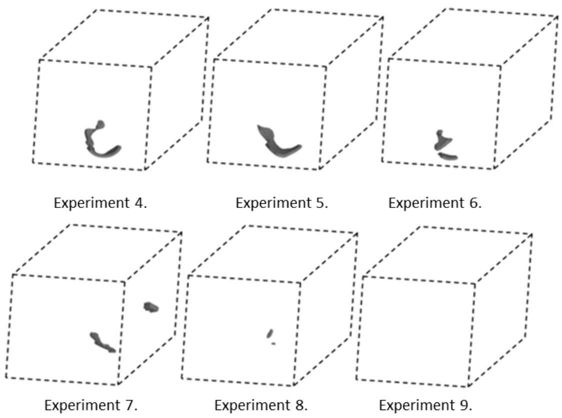

Figure 5
Entrapped air in the cavity

From the point of view of the adequacy of simulation the following factors played the main rules: tilting parameters, temperature values and die materials. The most important results of simulation, besides of the determination of technological parameters, are the identification of the critical process parameters.

- Geometrical adequacy: height of the pouring basin, cross-section of the basins' nose, geometry of the flow channel between the basin and the gating system.

- Pouring conditions: consideration of liquid contraction, cross-section of the melt stream, definition of pressure height to avoid splashing.
- Material properties and temperature adequacy: definition of the material and the temperature of the basin, application of refractory coatings to avoid melt cooling.
- Tilt conditions: filling stop criteria, rotation options, downtime after filling, time of tilt, tilt angle.

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