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Effect of inlet geometry on macrosegregation during the direct chill casting of 7050 alloy billets: experiments and computer modelling

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Abstract. Controlling macrosegregation is one of the major challenges in direct-chill (DC) casting of aluminium alloys. In this paper, the effect of the inlet geometry (which influences the melt distribution) on macrosegregation during the DC casting of 7050 alloy billets was studied experimentally and by using 2D computer modelling. The ALSIM model was used to determine the temperature and flow patterns during DC casting. The results from the computer simulations show that the sump profiles and flow patterns in the billet are strongly influenced by the melt flow distribution determined by the inlet geometry. These observations were correlated to the actual macrosegregation patterns found in the as-cast billets produced by having two different inlet geometries. The macrosegregation analysis presented here may assist in determining the critical parameters to consider for improving the casting of 7XXX aluminium alloys.

1. Introduction
Macrosegregation is one of major and irreversible defects in direct chill (DC) casting of aluminum alloys. Usually, the variation of the concentration of alloying elements throughout the cross section of the billet results in thermal and mechanical properties variation, which impair the quality of final products [1, 2].

The cause of macrosegregation is the relative movement of segregated liquid and solid during solidification [2, 3]. In DC casting billet of aluminum alloy, there are two main driving forces of this relative movement. The first one is convection flow in the liquid and slurry zones, such as thermosolutal convection (due to temperature and concentration gradients) and forced melt flow (e.g. pouring, stirring). The other is shrinkage-driven flow in the mushy zone. The later is due to the pressure difference over the solidifying layer of the mushy zone. Here the mushy and slurry zones are the two parts of the transition region during solidification corresponding to the different stages of solidification in DC casting of aluminum alloy. The limit between the two zones is the coherency isotherm. The condition of coherency can be defined as the moment when solid grains begin to interact with each other [5]. The slurry zone is the region between liquidus and coherency isotherm, where solid grains float freely. The region between coherency isotherm and solidus is called the mushy zone, where the macroscopic movement of solid grains is fully restricted.
Due to these driving forces, the extent of segregation in a real DC casting depends not only on the thermo-physical properties of the alloy but also on the actual casting parameters influencing the solidification process (e.g. casting speed, cooling rate and melt feeding). A proper correlation between casting parameters and the extent of segregation will help in determining the best casting practice, whereby a more uniform composition in the as-cast material can be achieved. Although invention and commercial use of DC casting could be dated back to the 1930s, and a number of studies both experimental and numerical [6-9] were dedicated to the effects of process parameters on the formation of macrosegregation, relatively little is known about macrosegregation under different melt flow feeding schemes.

The aim of this paper is to study the effect of inlet geometry on macrosegregation during the DC casting of 7050 alloy billets. Different melt feeding designs (melt distributor) were analyzed, combined with computer simulation of the solidification patterns, to obtain a full understanding of the evolution of macrosegregation during DC casting.

2. Experimental procedure and computer simulation
Two round AA7050 billets produced with different melt feeding schemes were selected in this research from industrial DC casting billets cast at Tata Steel Europe, The Netherlands. The casting temperature was around 680 °C. Both billets were grain refined by same amount of an Al5Ti1B master alloy. The diameter of cast billets is 315 mm. The melt was poured to the DC casting mold (without hot top) from the launder either through a semi-horizontal feeding distributor or a vertical feeding distributor, as shown in Fig. 1 (a) and (b), respectively. In the semi-horizontal feeding scheme, the melt was diverted to four branches through a cross-shaped splitter, while in vertical feeding scheme, all melt was poured directly in the center of the mold. The detail casting information at the steady state casting and the average alloy composition is shown in Table 1.

![Figure 1. Geometry of melt feeding distributors used in experiments: a, semi-horizontal melt feeding scheme; b, vertical melt feeding scheme. Half of the billet is shown. Centerline is on the left.](image)

| Table 1. The composition and casting parameters of selected billets |
|------------------|---------------|-------------------|-----------------|-----------------|
| Alloy            | Composition, wt% | Melt feeding scheme | Casting speed, mm/min | Casting temperature, °C | Cooling water flow rate, l/min |
| AA7050           | Cu 2.2  Mg 2.1  Zn 6.15 Zr 0.13 Ti 0.03 | Semi-horizontal | 50 | 680 | 40 |
|                  | Vertical      | 50 | 680 | 35 |

Slices of the cast billets were sawn at positions corresponding to the steady state stage of casting. The composition across the billet diameter was measured by a spark spectrum analyzer (Spectro, Kleve, Germany). The distance between each measured point is about 1 cm. After the composition measurement, the long striped sample was examined from the surface to the center in an optical microscope after being cut, ground, polished, and electro-oxidized at 20 VDC in a 3% HBF₄ water solution.
solution. Grain size was measured using the linear intercept method and the statistical analysis of the results was performed.

In order to analyze the sump profile and flow pattern in transition region under different melt feeding schemes, ALSIM6 was used. The simulated geometry consisted of the mold, water jet, bottom block and the casting moving domain (i.e. Arbitrary Eulerian Lagrangian description domain). In this 2D computer simulation, the heat, fluid flow, mechanical properties, casting and solidification modules were included in the ALSIM6 modelling set-up. The ALSIM program also calculates the heat transfer along the billet wall from the cooling water flow rate. The air gap formed between the mold and billet, which reduces the heat transfer, is also taken into account for heat transfer calculation. In average the heat transfer is found higher for the semi-horizontal feeding than for the vertical feeding geometry. The Naver–Stokes equations are solved in the model by considering a Darcy solidification term. Low Rayleigh number (LRN) turbulent energy–pseudoturbulent dissipation ($\kappa$-$\varepsilon$) model was chosen to solve the turbulence problem in this simulation. The velocity of the solid phase is equal to the casting speed throughout the transition region. A more detailed description of the software setup and models involved can be found elsewhere [10, 11]. The thermo-physical parameters for AA7050 alloy and mechanical database used in this simulation are given in Refs. [12, 13].

3. Results

In the semi-horizontal feeding billet, due to the inhomogeneous melt inlet caused by four inlets and potential implications for the macrosegregation, the composition was measured in three directions (at 45 degree angle from each other), The segregation patterns were similar, which attests for the negligible effect of this feeding scheme on the symmetry of the segregation. So in this paper, we only present the composition measurements from one diameter. The deviation of Cu, Mg and Zn concentrations from the average composition across the billet diameter are shown in Fig. 2(a). A negative central segregation for these elements can be observed. In the vertical feeding billet, as shown in Fig. 2(b), the maximum negative segregation for Cu, Mg and Zn appears 40-50 mm away from the center instead of strong centerline negative segregation. And also the extent of maximum segregation is getting lager as compared with the semi-horizontal feeding billet at the same casting speed. The Cu deviation almost reached 10 rel.%. At the chilled surface, a strong positive segregation can be observed in both semi-horizontal and vertical feeding billets. We can also see that the extent of deviation of alloying elements in both melt feeding schemes closely follows the magnitude of the partition coefficient. Such as partition coefficient for Cu is 0.17, which is far away from 1, results in a stronger segregation as compared with Mg, Zn, which partition coefficients are 0.43 and 0.45, respectively.

**Figure 2.** Deviation of alloying elements across billets diameter: a, semi-horizontal melt feeding billet; b, vertical melt feeding billet.

The grain size variation across the billet diameter is shown in Fig. 3. In the semi-horizontal feeding billet, the grains are coarser towards the center, while the minimum grain size was observed near the surface. The distribution of grain structure in the vertical melt feeding billet is totally different as compared to that obtained upon semi-horizontal feeding. The minimum grain size was found in the
center of billets. In addition, in the vertical melt feeding billet, a layer of coarser grains can be found around 40 mm away from the center, as illustrated in Fig. 4. The thickness of that layer is approximately 1 mm. The exact positions are shown in Fig. 3 with dashed lines. It should be mentioned that the presence of coarse grains near the center was not taken into account during measurement of grain size in Fig. 3 because this layer is too thin as compared with the whole billet diameter.

**Figure 3.** Grain size across billets diameter: a, semi-horizontal melt feeding billet; b, vertical melt feeding billet.

**Figure 4.** A typical layer of coarse grains near the center (40 mm away from the center) found in the billet with the vertical melt feeding. Coarse grains layer is shown in the dashed line area, see also in Fig. 3. Note that the length of Fig. 4 is only about 4 mm.

**Figure 5.** Simulated sump profiles and flow patterns during DC casting: a, semi-horizontal melt feeding billet, maximal magnitude of velocity around melt inlet area is 2.4 mm/s; b, vertical melt feeding billet, maximal magnitude of velocity around melt inlet area is 30 mm/s. Centerline is on the left.

Sump profiles and flow patterns in the billet were simulated for both melt feeding schemes, as shown in Fig. 5. In the billet cast with semi-horizontal feeding (Fig. 5(a)), the slope of solidification front is relative gentle. The sump depth in the center (from the melt level in the mold to the solidus) is about 12 cm. The movement of solid and liquid phases (velocity) in the liquid and in the transition region is most intense near the surface, while a moderate upstream flow can be observed in the center. In the billet cast with vertical feeding, vertical melt flow inlet in the center causes a cliff-shaped sump, as shown in Fig. 5(b). The slope increases dramatically at the position 40 mm away from the center. The solidification front drops vertically and the solidification rate at this point is almost zero. The sump depth in the center is about 17 cm. The flow is more pronounced and directed downwards in the center and upwards off-center instead of being intense near the surface as in the case of semi-horizontal feeding. More details about sump profiles and flow patterns in these simulations will be discussed in the next section.
4. Discussion

4.1. Relative movement of melt flow in slurry zone

It is well known that the convection flow in the liquid and slurry zone results in the redistribution of alloying element in the DC casting billet. The velocity patterns of this convection flow are shown in Figs. 5(a) and (b). Fig. 6 gives the melt velocity in the slurry zone across the billet from the center to the surface. The solid fraction at coherency is taken as 0.5 for our alloy, because both billets in this research are grain refining. The flow velocity in the slurry zone shown in Fig. 6 is taken around the 0.4 solid fraction isoline.

As shown in Fig. 5(a) and Fig. 6, in semi-horizontal feeding billet, the penetration of melt flow into the slurry zone is more pronounced near the surface area. This means that the effect of washing out of solute-rich liquid from the slurry zone in this area is larger than in the quarter and center of the billet. This solute-rich liquid moves then towards the quarter and central areas along with the convection flow, which results in the lack of alloying elements near the surface area and the positive segregation in the quarter position.

In the vertical feeding billet, the flow pattern changed totally because of different melt inlet (Fig. 5(b)). There are two convection flows as illustrated in Fig. 7. One is near the center area, counter-clockwise. Another is at the quarter and surface of the billet, in the clockwise direction. Two flows collide at the position 40-50 mm away from the center. As we can see from Fig. 6, the most pronounced washing out of solute-enrich liquid from the slurry zone happens around the cliff-shaped solidification front (40 mm away from the center). This strong upstream flow in the slurry zone might wash out the enriched solute either to the center or to the surface area, which causes negative segregation in this area, as shown in Fig. 2(b). It should be mentioned here that it has been reported that strong forced unidirectional flow in the center may cause a consistent change of the concentration along the billet axis, which can be detected in the last stages of casting [14]. However, in this research, we only selected one slice for each billet in the middle of steady state casting and did not take this effect into account.

4.2. Relative movement of solid grains in slurry zone

The movement of solid grains along with convection flow is one of the mechanisms of macrosegregation. The ‘floating’ grains, which form at earlier stage of solidification, are usually depleted of the main alloying elements in Al alloys such as Cu, Mg, Zn. These grains float with convection flow and usually settle in the center of DC casting billet, causing centerline negative segregation [15].

In this research, we could not find any typical ‘floating’ grains in both the semi-horizontal and vertical billets. However, a layer of coarse grains found in the vertical melt feeding billet (Fig. 4) is
really interesting and might be related to near-center negative segregation (40 mm away from the center) in Fig. 2(b) if we interpret this phenomenon as follows.

Fig. 7 is the schematic view of cliff-shaped sump in the vertical melt feeding billet. A cliff-shaped sump leads to an almost vertical solidification front approximately 40 mm away from the center. The grains, which are formed in the slurry zone around this vertical solidification front or formed earlier at other position then arrived in this area with melt flow, will stack and grow at the same position of almost vertical solidification front because of strong upstream melt flow and gravity. It also worth to notice that in Fig. 5(b), there is a collision area of clockwise and counter-clockwise flows, as mentioned before. In this area there is almost no horizontal velocity component. In this case, solid grains cannot be displaced from that cliff-shaped front due to stack of grains, but solute enriched melt can. As a result, the strong upstream flow will continue to take the solute enriched liquid away from this slurry zone but leave the solute depleted grains. This might enhance negative segregation in this cliff shaped sump area (40 mm away from the center).

4.3. Solidification shrinkage-driven flow in mushy zone

As an important mechanism of macrosegregation, the solidification shrinkage-driven flow in the mushy zone usually determines the inverse (negative) centerline segregation in DC casting billets of aluminum alloys. This shrinkage flow is caused by the pressure difference over the solidifying layer of the mushy zone, which results in the movement of the solute-rich liquid to the deeper part of mushy zone in the direction perpendicular to the solidification front.

A simple analytical model was suggested by Du and Eskin in order to analyze the effect of the mushy zone geometry on the degree of shrinkage-induced macrosegregation in DC casting aluminium alloy [16]. In this research, we used this model to make a simple analysis for segregation of Cu (Mg and Zn follow the same trend) and the effect of melt inlet on shrinkage-induced macrosegregation.

The main idea of this model is that the centerline negative segregation is caused by the horizontal component of the shrinkage-driven flow from the center to the surface of the billet. By taking solidification shrinkage and solidification front inclination into account, the total amount of the transferred solute at different positions during the solidification period ($L_m/V_{cast}$) is as follows [16]

$$L_h = \int_0^{L_m/V_{cast}} C_l f_l V_{cast} \beta (\sin 2\alpha) / 2 \, dt$$

(1)

Where $V_{cast}$ is the casting speed; $\beta$ is shrinkage ratio (0.1 for an aluminum alloy); $\alpha$ is the local slope of the coherency isotherm; $L_m$ is the vertical thickness of the mushy zone; $C_l$ is liquid phase concentration; and $f_l$ is the volume fraction of liquid phase. This equation can be reduced for Cu (partition coefficient $k_{Cu}$ is taken as 0.171) to [16]

$$L_h = 0.78 C_{f_l} L_m \beta (\sin 2\alpha) / 2$$

(2)

The derivative of Eq. (2) $dL_h/dr$ ($r$ is the radial distance from the billet center) is the net efflux and is a measure of the macrosegregation caused by solidification shrinkage. The detail derivation of these equations can be found in Ref [16].

Fig. 8(a) is the distribution of transferred solute $L_h$ from the center to the periphery of the semi-horizontal feeding billet. This curve represents the balance between the amount of solute coming to one point and the amount of the solute coming out of this point. When the slope is positive, the incoming solute is less than out-coming solute, which causes negative segregation at this position by shrinkage driven flow. On the contrary, the negative slope results in positive solute income at this position. Fig. 8(b) is the relative segregation of Cu ($-dL_h/dr/C_{Cu}$), obtained by the derivative of the polynomial fit shown in Fig. 8(a) with respect to radial distance from the center of semi-horizontal billet (with the negative sign). It is clearly shown that shrinkage driven flow causes a negative segregation in the center of the billet until the position 60 mm away from the center, then a positive segregation occurs. Near the surface of the billet, the segregation changes to negative again.

If we compare the calculated shrinkage-induced segregation in Fig. 8(b) with real Cu segregation distribution in the semi-horizontal feeding billet (Fig. 2(a)), a good agreement on the distribution of Cu segregation can be found. It should be noted that the segregation curve in Fig. 8(b) reflects only the
calculated segregation caused by shrinkage-driven flow. As discussed before, the movement of solute-enrich liquid in the slurry zone from the surface to the center contributed to a centerline positive segregation. Taking into this account, negative 6.5 rel.% deviation of Cu in the center caused by the shrinkage flow (Fig. 8(b)) might be compensated by the effect of convection flow in the slurry zone. As a result, the negative centerline segregation in the real casting billet reduces to about 4 rel.%, as shown in Fig. 2(a).

Figure 8. Effect of shrinkage driven flow on macrosegregation in the semi-horizontal melt feeding billet: a, amount of transferred solute from the center to the surface and its polynomial fit; b, relative segregation caused by shrinkage driven flow, obtained by the derivative of the polynomial fit

Figure 9. Effect of shrinkage driven flow on macrosegregation in vertical melt feeding billet: a, amount of transferred solute from the center to the surface and its polynomial fits; b, relative segregation caused by shrinkage driven flow, obtained by the derivative of the polynomial fit

Same analysis has also been done for the vertical melt feeding billet. Fig. 9(a) is the distribution of transferred solute $L_h$ from the center to the periphery of the vertical feeding billet. Due to relatively complex distribution of $L_h$, we divided the distribution in Fig. 9(a) into two parts and made the polynomial fits separately in order to increase fitting accuracy. By the derivative of $L_h$ distribution in Fig. 9(a), we can also obtain the relative Cu segregation from the center to the surface of the vertical feeding billet, as shown in Fig. 9(b). The agreement between shrinkage-induced segregation in Fig. 9(b) and real segregation distribution in Fig. 2(b) is not as good as in semi-horizontal feeding billet. But we still can see that there is an obvious negative segregation at the position 40-50 mm away from the center, which shows the shrinkage driven flow might also contribute to the strong near-center negative segregation in addition with the convention flow and “floating” grains as discussed above.

The shrinkage driven flow also causes a positive segregation at the position 25-40 mm away from the center, as shown in Fig. 9(b). Although the positive segregation in this area does not appear in real segregation curve in Fig. 2(b) (though a slight increase in the concentration can be observed), it becomes logical when the melt flow in slurry zone is considered. This positive segregation area caused...
by shrinkage driven flow coincides with the position where a strong upstream flow is. Therefore the liquid near the coherency isotherm could be already depleted by this upstream flow and might not be rich enough to allow the shrinkage driven flow to create such a positive segregation. In addition, the redistribution of solute to the surface area in combination with a flat region of almost no shrinkage-induced segregation (from quarter to the surface of the billet), leads to a positive segregation in this region, as shown in Fig. 2(b).

As for the strong positive segregation at chilled billet surface we observed in both billets, similar results have been reported elsewhere [6, 15, 17]. It is a result of shrinkage driven flow toward to the chilled surface, where there is no out-coming flow. Thus, the solute will accumulate at the chilled surface and usually lead to a negative segregation in the sub-surface region, as shown near the surface area in Fig. 2 (a) and (b).

5. Conclusions

The melt inlet feeding scheme influences the macrosegregation in DC casting AA7050 billets by changing the flow patterns and sump profiles during casting. The solute-rich liquid washed out from the slurry zone by convection flow usually leads to the lack of alloying element in this area and an accumulation of solute downstream of this convection flow. The shrinkage-driven flow in the mushy zone is the dominant mechanism to determine the centerline negative segregation in a DC casting AA7050 billet. However, the final macrosegregation in casting billets is a clear result of a combination effect of convection flow in slurry zone and shrinkage-driven flow in the mushy zone. The relative movement of solid grains with melt flow also might play a role on macrosegregation in some local areas.

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