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Surface formation in direct chill (DC) casting of 6082 aluminium alloys

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Abstract. Surface defects in aluminium billet production are a real problem for the subsequent extrusion procedure. Extrusion productivity can be influenced by the surface properties, which is defined as surface appearance, surface segregation zone depth and large Mg\textsubscript{2}Si and \textbeta-particles (Al\textsubscript{5}FeSi). In this research the surface formation during DC casting of 6082 aluminium billets produced by the air slip technology is studied. The surface microstructures of 6082 aluminium alloys with smooth and wavy surface appearances were investigated, including segregation zone depths and phase formation. The results were discussed based on the exudation of liquid metal through the mushy zone. The specific appearance of the wavy surface of 6082 alloys was correlated to how the oxide skin adheres to the underlying mushy zone and coupled to the dendritic coherency and surface tension of the skin. The occurrence of different phases at the very surface and in the layer just below was explained by variations in solidification directions and subsequent segregation patterns.

1. Introduction
The 6xxx series Al alloys are basically produced for extrusion. Among 6xxx alloys, the 6082 with high content of magnesium and silicon is the strongest alloy with widespread applications in building, aircraft and automotive industry [1]. The surface zone of the mentioned alloy, when produced by direct chill (DC) casting, has an important role on the quality of the extruded materials. Although the introduction of the air–slip technique in DC casting has improved the surface quality to some extent, strong variations in surface appearance and surface defects can be found in this alloy type [2–4]. The depth of the surface segregation should also be considered as an important factor in surface quality, and can be defined as a layer in which the alloy contents deviate from the bulk [5, 6].

In the recent paper [7] the surface formation in low-alloyed 6000 series alloys was investigated. In the present paper the study is extended to the more highly alloyed 6082 with a more severe surface segregation, and the different types of surface appearances and phase formations are discussed.

2. Experimental procedure
Microstructures and surface segregation from 6082 Al alloy billets, 178 mm diameter, with banded or wavy–defect surfaces were compared to defect free or smooth surfaces. The compositions of mentioned alloy are given in table 1, and grain refiner in shape of Al-5Ti-1B master alloy at a level of 1 Kg/tonne had been added. Metallographic samples were cut at the surface and along the growth direction to show the structure of the surface zone. The surface segregation and occurring phases were studied by light optic microscope (LOM). A scanning electron microscope (SEM) was used to observe the transverse cuts, but also to study unprepared surface structures directly on the billet surfaces. The secondary phases were analysed by energy–dispersive X-ray spectroscopy (EDX). A part of the
surface with a wavy appearance was deeply etched in a solution of methanol, iodine and tartaric acid to partially dissolve the aluminium matrix to give a better view of the secondary phase distribution. Stereo light microscope (SLM) was also used to study the surface appearances.

| Table 1. Chemical composition of 6082 aluminium alloy in wt%.
|---|---|---|---|---|---|---|---|---|
| Alloy | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  |
| 6082  | 0.96| 0.19| 0.001| 0.46| 0.63| 0.0006| 0.002| 0.011|

3. Results
In figure 1, the SLM images of smooth surface of 6082 alloys and wavy samples surfaces of 6082 and 6060 alloys are shown. It is clear that the wavy 6082 surface has an irregular pattern and the distances between waves are not constant, as could be observed in low-alloyed of 6xxx series [7].

![Figure 1](image)

Figure 1. The stereo light microscope images: a) Smooth surface; and b) Wavy surface for 6082 alloy and c) Wavy surface for 6060 alloy [9].

On many places the surface is bulged out between points and patches in the transverse direction, i.e. in a band-like pattern without forming bands.

Figure 2 illustrates the surface segregations are defect free and wavy-defect surfaces. At the defect free surface the segregation thickness is more uniform and about 50-80 μm, while the surface segregation depth in the wavy sample is 50-150 μm. It is clear from the figure that the surface segregation depth at the wavy surface is clearly not uniform, and also the phases occurring in this zone are different.

Figure 3 illustrates the surface microstructures viewed by SEM directly on the outer surfaces. In figure 3a the microstructure of a defect free billet can be observed. Light phases in plate-like (fan shaped) morphology are dominating at the smooth surface all over the surface and only a few other phases can be seen randomly. The corresponding surface in the transverse cut is shown in figure 2a and b, where the plate–like structure can be seen growing out towards the surface in the cell boundaries. Figures 3b shows a wavy surface structure and it is obvious that different phases dominate at different positions along the waves.

In figure 4 results from EDX analysis of different intermetallic phases are shown. The plate-like structure (figure 4a), which dominates the smooth surface, but occur on all surfaces, has a Fe:Si ratio (atomic %) of about 1:2. The phases in figure 4b and 4c can also be found in all surfaces but are more frequently seen in the wavy surface, the ratios are (Fe,Mn):Si (atomic %) 1.5:1 and Mg:Si 2.3:1 in 4b and 4c, respectively. In figure 4d, where a secondary phase is filling out the cell boundaries, the (Fe,Mn): Si ratio (atomic %) is about 1:1.

Figure 5, shows the same sample after deep etching where it can be seen how a secondary phase in a dendritic like morphology, has been grown in the intercellular areas and out on the surface.
Figure 2. Transverse cross section of 6082 Al alloys a, b) Defect free surface along growth direction; c, d) wavy surface along growth direction.

Figure 3. SEM untreated surface images of a) smooth surface; and b) wavy – defect surface.

4. Discussion
At smooth surfaces the segregation zone has a relatively constant thickness, Figures 2a and b, indicating that this type of surface is obtained when the pressure fluctuations in the melt, and thus the meniscus movements, are minimized. At such conditions, the melt uniformly exudates from the mushy zone to the layer between the oxide skin and the coherent solid [7].

In a previous study [7] it was shown that the segregation zone thickness of 6060 and 6005 alloys are 50-70 μm and 120-150 μm, respectively. The mentioned alloys have lower alloy contents than 6082, and it can therefore be expected that 6082 should have a thicker segregation zone. However, the results here show a zone thickness for 6082 of the same level as for 6060 but thinner than for 6005, which have an intermediate alloy level. In a comparison of these alloys the amount of secondary phases, eutectic structures and alloy contents [5] in the surface zone increase with alloy content, but the thickness of the layer does not. This might be explained by the fact that all alloys end with eutectic solidification at about 557 °C, and although the amount of eutectic increases, the solidification interval decreases for the higher alloyed 6082, figure 6. A factor influencing the thickness of segregation zone is also the metal head height [8], which might have varied for the studied billets.

When an unsmooth surface like the one discussed above is formed, a so-called wavy surface, as in Figure 1b can occur. The surface has irregular grooves and bulged zones, which occur in a
semi-periodic pattern. Due to metal head pressure changes the meniscus movements will form a wavy - defect surface [7, 9]. Surface tension forces and pressure differences will define the curvature of the meniscus, and increasing surface tension coefficient will decrease the surface curvature [10]. In [7] the formation of surface zone during casting of a billet of 6005 and 6063 Al alloys were discussed, and exudation of alloying elements through the mushy zone was described. Exudation of liquid with high alloying content will affect the surface tension and the plasticity of the meniscus at mushy zone. For instance, it is reported that more than 0.2% of Mg can lead to the formation of MgO instead of Al$_2$O$_3$, and MgO seems to be weaker than Al$_2$O$_3$ [3]. While the billet is moving downwards the surface tension changes and gravitational forces over the meniscus will no longer be balanced, and at some point liquid will flow over the solid shell. This type of irregular wavy defect can occur in 6082 Al alloys, while the formations of waves on 6060 and 6005 alloys are more regular [7]. This irregular appearance might look as if exudated liquid is pressed out on the oxidized surface and solidified in an irregular way. However, studying the cross sections along many surfaces it is clear that liquid never exudates out through the oxide skin, see e.g. figure 2d. This type of surface only occurs in more highly alloyed 6xxx alloys in contrast to e.g. 6060, which show a very regular banding or lapping pattern, as in figure 1c, [7, 9, 10]. The difference can be explained by differences in coherency points for these alloys. When the meniscus fluctuates, and a wavy surface is formed the oxide skin moves inwards over the mushy zone during low liquid pressure [7]. At this movement, in a low-alloyed billet, the oxide skin will effectively adhere to a rigid coherent semi-solid and form a ring contact. If the solid fraction is under the coherency point, as in a high alloy billet, the oxide skin will adhere more randomly, i.e. in patches, points or shorter lines as in figure 1b. When the pressure increases the oxide skin is bulged out, and in the low-alloyed case a perfect ring droplet will form, while in the high alloy case the oxide skin is pressed out irregularly between the contact points. The differences in the coherency point can be seen in figure 6, where the solid fractions as a function of temperature are shown from thermodynamic calculations, (JMatPro). The coherency point for these class of alloys are in the solid fraction of about 0.5 [11], which means that it will occur at 650 °C for 6060 but at 640 °C for 6082.

In figure 5, eutectic α-phase, growing from the intercellular areas up to the surface, can be seen, but there is no connection to surface phases. It can therefore be concluded that the surface phases rather loosely has grown in the surface layer. The phases shown in figure 3, a and b, and in figure 4, a, b, c and d, are found on the surface of the billets when using a SEM. Similar observations have been done on other 6xxx alloys in [7, 8] but the formation of these top surface structures have not been satisfactory explained. In [7] the plate-like phase was identified as β-phase, Al$_3$FeSi, and the dendritic phase as α-phase, Al$_5$(Fe,Mn)$_3$Si$_2$. This can also be confirmed in this study as the Fe:Si ratio is 1:2 in the plates in figure 4a and the (Fe,Mn):Si ratio is 1.5:1 in the dendrites in figure 4b. The third phase, also in a dendritic pattern but with a weaker contrast, figure 4c, has the Mg:Si ratio 2.3:1, which indicates Mg$_2$Si phase. The phase occurs rather frequently and on many places together or below the other phases, as can be seen in figure 4b. In figure 5 an attempt was made to show how the surface phases are connected to the structure in the intercellular spacing’s. In [7] the outwards solidification of the exudated melt to a top most layer of about a few microns was discussed, and strongly increasing solute concentrations were concluded.
The shapes of the phases, i.e. plates or dendrites that have grown in that layer indicate that they grow as primary precipitations but the growth is not followed by a eutectic growth to finalize the solidification. Instead, the thin liquid layer with the last melt will be sucked down between the cells due to solidification shrinkage during the final stages of the solidification. As it is illustrated in figure 3b, different phases can be observed on the wavy surfaces. Also the structures in the cross sections, figure 2d, show the variations on a place where the surface starts to bulge out. In a short section to the right a structure similar to a smooth surface can be seen with a cellular structure growing outwards and with mostly β-phase in the cell-boundaries. Then from the right to the left the surface is pushed out and there eutectic areas with α-phase dominate. In such regions, occurring around patches and point contacts, the structure indicates a more equiaxed growth, as there is no clear outward directed cell structure. It may be so that during the outwards cellular growth the segregation gives a higher Si
content, and thus more β-phase is formed in cell-boundaries and on the surface, while the bulged out areas solidifies more equiaxed with larger eutectic areas between grains in which α-phase dominates.

5. Conclusions
Smooth surfaces and surface segregation zones of uniform thicknesses are obtained when the pressure fluctuations in the melt, and thus the meniscus movements, are minimized.

The surface segregation zone thickness in 6082 alloys, for both smooth and wavy surfaces, is not wider than for 6060 and 6005 alloys but the amount of solute and secondary phases in this zone is larger.

The formation of the specific surface appearance on wavy 6082 surfaces can be correlated to how the oxide skin adheres to the underlying mushy zone.

In 6082 alloys the phases Mg$_2$Si, alpha and beta were observed in the surface zones of all studied surfaces but the extent of the different phases vary with surface appearance. At smooth surfaces beta is dominating, while at wavy surfaces, especially at the rim of bulged areas, alpha and Mg$_2$Si are more frequently appearing.

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