The Formation of Segregation Bands in AI-Si Castings

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Abstract

Bands of defects are commonly found in high pressure die cast (HPDC) aluminium alloys. In the work presented here, similar defects have been observed in laboratory gravity die castings. Castings were poured with an initial solid fraction in the range f_s = 0-0.3 to simulate the externally solidified crystals (ESCs) injected in cold chamber HPDC. The effect of the fraction of ESCs on the segregation bands at die temperatures in the range 130 – 450°C was investigated. In addition, the behaviour of the ESCs during filling has been studied. A mechanism describing the formation of the segregation bands has been proposed by considering flow past a solidifying wall layer accounting for mushy zone dynamics and rheology.

1. Introduction

In cold chamber HPDC, the material injected into the die often contains a fraction of primary crystals. These form when superheated metal impinges on the relatively cold shot sleeve wall and plunger during pouring into the shot sleeve and thus semi-solid is injected into the die [1, 2]. These externally solidified crystals (ESCs) commonly have a volume fraction (f_s^{ESC}) in the range 0.1- 0.3 [2]. After injection, further solidification occurs from the relatively cold die walls during filling so that flow and solidification occur concurrently.

A typical HPDC microstructure contains a dense region of ESCs at the centre of the crosssection with regions of largely ESC-free material nearer the surface [1, 3] (Figure 1a). It has been suggested that fluid-dynamic forces cause the ESCs to migrate to the region of lower stress (towards the flow axis) during filling [3], but the exact mechanisms for this remain unexplored. Another striking feature of HPDC microstructures is the presence of banded defects. These bands contain segregation, porosity and/or tears and follow the contour of the casting [4, 5]. In HPDC AI alloys, segregation bands are common, containing a higher fraction of eutectic than the surrounding material (Figure 1b). The position and appearance of these bands are affected by changes in casting conditions and depend on the alloy used.

Whilst some researchers [5, 6] have attempted to study banded defects by changing parameters in commercial die casting processes, the complex, dynamic nature of these processes has prevented individual parameters from being isolated and studied in detail. In the work presented here, gravity die castings are found to contain both segregation bands similar to those in HPDC and also centred ESCs. Bands have therefore been studied using controlled laboratory gravity die casting experiments.





Figure 1: Microstructures from a commercial A356 HPDC 'U' shaped box [1]: (a) a dense region of ESCs (white grains) at the centre of the cross-section and (b) segregation bands following the contour of the casting.

2. Experimental Procedure

A commercial A356 alloy (Al-7wt%Si-0.3wt%Mg) was used throughout the study. A 1kg melt was cooled from 700°C in air whilst being stirred at 600 rpm with a Boron Nitride coated impeller to break-up the solid phase. When the desired temperature, measured by a K-type thermocouple, was reached, the semi-solid was poured into a pre-heated steel die (Figure 2a). The solid fraction was calculated using the Scheil equation. The die was tilted at an angle of 8° to assist flow and has an open end to allow flow through the die. Semi-solid was continuously poured into the die until flow arrested by solidification. No die coat was used to minimise the resistance to interfacial heat transfer and also to simulate HPDC conditions. Solid fractions from $f_s= 0$ to 0.3 were used (similar to those in cold chamber HPDC) at different die temperatures (130 – 450°C).



Figure 2: a) The open ended elbow-shaped die of side 120mm. b) Samples were taken from plane A.

The castings were sectioned through plane A, as indicated in Figure 2b. Throughout this paper "the cross-section" will refer to plane A. Samples were ground and polished before being electrolytically etched with a 5% HBF_4 solution.

3. Results and Discussion:

A typical microstructure of the gravity die casting cross-section is shown in Figure 3a. Note that it contains both a segregation band and also centred ESCs (the large white grains) in a similar manner to HPDC microstructures (Figure 1a and b).



Figure 3: Macrographs of segregation bands in gravity die-cast A356. a) cast at 16% solid into a 270° C die and b) cast with 7°C superheat into a 200° C die.

3.1 Externally Solidified Crystals (ESCs)

As a result of stirring, the ESCs have a rosette-like morphology (Figure 4). At the centre of the casting they are partially agglomerated and are often surrounded by pools of eutectic, which probably originates from entrapped liquid.

In all castings, the ESCs were more densely packed at the centre of the cross-section (Figure 5). The local fraction of ESCs at the centre was found to be between 0.35-0.4 for all bulk f_s^{ESC} used. This is slightly above the reported coherency point of rosette-shaped grains [7] so it is likely the ESCs formed an interconnected network during filling. It is proposed the ESCs in the central network flow with the same velocity and behave as a visco-plastic plug. Those ESCs which are not part of the ESC network are probably carried in the liquid as a suspension. With increasing f_s^{ESC} , the area of the cross-section covered by the ESCs was found to increase until at f_s^{ESC} =0.3, the ESCs are almost distributed evenly in the cross section (Figure 5). However, irrespective of the f_s^{ESC} , a layer containing no ESCs was always observed at the casting surface.



Figure 4: a) A typical micrograph from the centre of a casting. Rosette shaped crystals are partially agglomerated and interconnected. b) The first metal to flow from the crucible contains a similar ESC fraction.

In order to verify that the solid was evenly distributed and had not settled in the crucible before pouring, the first metal to flow out of the crucible was quenched and examined. Figure 4b shows that this material contains a qualitatively similar f_s^{ESC} as the bulk material, and suggests that the lateral movement of solid has occurred during flow in the die.



Figure 5: Macrographs showing that the area covered by ESCs increases with increasing fraction of ESCs (f_s^{ESC}). f_s^{ESC} = a) 0.07, b) 0.16, c) 0.22, d) 0.3

3.2 Segregation Bands

In general, the band is made up of material with a higher fraction eutectic than the surrounding material. This is shown in Figure 6a where there is a broad peak in both silicon concentration (found using EDS in an SEM) and area fraction eutectic (calculated by quantitative metallography) in the 3mm from the bottom of the cross-section.



Figure 6: a) The variation in fraction eutectic (solid line) and at%Si (dashed line) with distance from the edge. b) Variation in band position with die temperature for $f_s^{ESC} = 0.16$.

Within the band there is evidence of interconnected eutectic pathways and features such as flow or slip paths (Figure 7a). Tributaries of eutectic have also been observed leading from the inner material to the band suggesting liquid segregated to the band (Figure 7b).



Figure 7: (a) Pathways due to the flow of enriched liquid or slip paths due to dendrite network collapse. b) Pathways of eutectic leading from the inner material to the band as tributaries. $f_s^{ESG} = 0.16$, die T = 270°C

For a given f_s^{ESC} , the band position (the distance from the bottom of plane A to the centre of the band) decreases with increasing die temperature in the manner shown in Figure 6b.

3.3 The Effect of fs^{ESC} on Segregation Bands:

Figure 3b shows that segregation bands form even when no ESCs are present which indicates that ESCs are not an essential part of the band formation mechanism. However, increasing the f_s^{ESC} moves the band towards the edge in the manner shown in Figure 8. With increasing f_s^{ESC} , the band position



moves closer to the surface and the area covered by ESCs also expands outwards (Figure 5). However, it is important to note that the band moves outwards at a greater rate than the ESC plug and that the band forms a significant distance from the edge of the ESC plug in some castings (typically 1-2mm) suggesting the increasing size of the plug is not solely responsible for the change in band position.

4. Mechanism of Band Formation:

The evidence of flow and slip in the segregation band (Figures 7a & b) suggests the band forms within a semi-solid network during filling. It is proposed that solidification at the die walls during flow will result in an immobile layer attached to the die walls. This layer contains a solid fraction gradient. Material at the die wall has the highest solid fraction and material at the edge of the wall layer contains a solid fraction corresponding to a solid network that can just resist the hydrodynamic forces caused by flow past the immobile layer. As the layer is semi-solid, it is saturated with liquid. The bulk flow past the wall layer causes interdendritic flow through the solid network.

Within the immobile solid fraction gradient, the microstructure changes as the solid fraction increases towards the die wall; the dendrites become coarser, more closely packed and more interlocked, and the local strength of the network increases [8]. Furthermore, the velocity profile due to flow results in an increasing shear stress towards the die wall (away from the flow axis). At the same time, the local permeability of the network decreases towards the die wall and interdendritic flow becomes more difficult and tortuous.

It is proposed that a critical fraction solid exists within the solid fraction gradient at which the local interdendritic flow rate is unable to equal the deformation rate caused by the bulk flow. If the shear stress at this point exceeds the local strength of the dendrite network, local slip occurs in the network. Slip in the network would cause some interdendritic regions to increase in volume, creating a pressure drop. Liquid with an available path can then be drawn into the slipping region. In this way enriched liquid is forced to the fraction solid contour where slip events occur. This mechanism has been observed in shear cell experiments on similar alloys where liquid was found to segregate to the slipped region as grains rearranged away from the plane of slip [9]. The material between the die wall and the band is likely to be sufficiently strong to resist deformation viscoelastically. This mechanism is shown schematically in Figure 9.

The enriched liquid in the regions of slip contain a high fraction eutectic, thus forming a distinct band. A lower die temperature will result in a thicker wall layer during flow, so the critical fraction solid will move away from the die wall. Figure 6b shows the band to move away from the die wall with decreasing die temperature.

The ESC plug is not an essential part of the formation mechanism of the band, but affects the position of the bands. It is proposed the main effect of an increasing f_s^{ESC} is to increase the apparent viscosity of the mobile material.



Figure 9: A schematic diagram showing a solid fraction gradient emanating from a die wall (downwards). Flow is from left to right. The response of different regions to the applied stress is shown:

Network collapse occurs at a contour where the interdendritic flow rate is unable to equal the deformation rate and the solid network is weaker than the applied stress.

5. Conclusions

Segregation bands and centred externally solidified crystals (ESCs) similar to those found in commercial cold chamber HPDC aluminium alloys have been witnessed and studied in gravity die castings. ESCs have been found to migrate to the centre of the cross-section where they form a solid network. An ESC-free zone always exists at the surface of a casting for any bulk fraction of ESCs.

Segregation bands contain a greater fraction of eutectic than the surrounding material and evidence of flow and slip within a dendrite network has been observed in the bands. Bands have been found to move closer to the casting surface with increasing die temperature and increasing fraction of ESCs. A formation mechanism has been proposed based on flow past an immobile solidifying wall layer.

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