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Gate microstructure in an AlSi9MgMn High-Pressure Die Casting

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The high-pressure die casting of ductile Al alloys has become widespread in the manufacture of structural automotive components. This paper examines the gate microstructure to investigate how material is transported into the die cavity during the intensification stage. Bands of positive macrosegregation, with the features of semi-solid shear bands, are shown to be present in the runner, through the gate and into the casting. The results are compared with a past study on the role of intensification pressure on gate microstructure to show that semi-solid shear banding through the gate acts as a feeding mechanism in HPDC. The study focuses on an AlSi9MgMn thin-walled U-shaped casting from a multi-gated die. The marked difference between this alloy and die design compared to the past study suggests that semi-solid shear banding through the gates during the intensification stage is most likely a general feature in Al-alloy HPDC.

Keywords: *macrosegregation, defect bands, intermetallics, gate, intensification pressure*

1. Introduction

In recent years, aluminium high-pressure die-casting (HPDC) has become increasingly used to manufacture structural automotive components, with typical applications including shock-towers and ‘A’ and ‘B’ pillars [1]. This has been facilitated by improvements in the HPDC process and the adoption of HPDC-specific aluminium alloys. The attraction of HPDC comes from the capability of mass-producing large, integrated parts in a single-step, which offers the potential for reducing cost and energy consumption in manufacturing while decreasing the mass of vehicles. However, HPDC can be prone to high levels of defects if the alloy, die design and HPDC parameters are not optimized. Of particular importance in producing adequate components, is minimising air entrapment during both filling stages and ensuring that material can be fed through the gates into the die cavity during the feeding stage.

Die design in HPDC typically includes gates that are significantly narrower than the runners to ensure a high metal flow rate during cavity filling. Once the filling stage is complete, all feed material must be transported through the relatively thin gates because HPDC dies rarely have feeders/risers. Since the gates are thinner than adjacent regions, they have a higher mean solid fraction than the runners and casting at an equivalent time in the intensification stage, and the ability for material to be transported through the gates in the latter stages of HPDC therefore plays a key role in determining the effectiveness of feeding solidification shrinkage and thermal contraction, and compressing any entrapped air.

It is well established that increasing the intensification pressure usually decreases the porosity level [2-4], but little research has been dedicated to the mechanisms controlling material transport through the gates during the latter stages of HPDC. A recent study examined HPDC gate microstructures after casting with different levels of intensification pressure (IP) [5]. It was shown that the gate microstructure changes significantly depending on the applied IP, in the range ~0 – 60 MPa. Above a critical IP, a marked decrease in porosity was observed. At a similar value of IP, semi-solid shear banding was found to occur through the gate. These bands had the characteristics of defect bands commonly found in HPDC parts [6-8] and it was suggested [5] that partially-solid shear banding through the gate during the IP stage plays a significant role as a feeding mechanism by creating weak shear zones that assist in transporting material through the gate into the casting.

This research [5] was conducted on AlSi3Mg and AlSi4Mg alloys using a single-gated casting where the gate was significantly narrower than both the runners and the casting (~4 times narrower). To examine whether the feeding mechanisms deduced in that study are general to HPDC or specific to the alloy/die-geometry used, this paper investigates the gate microstructures of an AlSi9MgMn alloy cast in a multi-gated die where the gate thickness is approximately half the casting thickness.

2. Experimental Methods

The widely used HPDC alloy, AlSi9MgMn, was selected for this study. Casting was performed on a Buhler 4.1MN locking force cold-chamber HPDC machine. The die used was that described in [9], which has ten gates, each with thickness 1 mm, and produces the thin-walled (2 mm) 'U' shaped profile shown in Fig. 1. This die is an analogue for industrial dies creating thin-walled structural automotive parts such as 'B' pillars and shock towers. The die was maintained at ~200ºC by pumping oil through channels in the die. The melt was degassed using Ar and then transferred to the shot chamber with a melt superheat of ~80 ºC. The slow shot phase was conducted at 0.3 ms^{-1}, the die-filling phase at 4 ms^{-1}, and an intensification pressure of 60 MPa was then applied. The results presented in this paper were obtained from a casting produced after a quasi-steady-state temperature had developed in the shot-chamber and die.

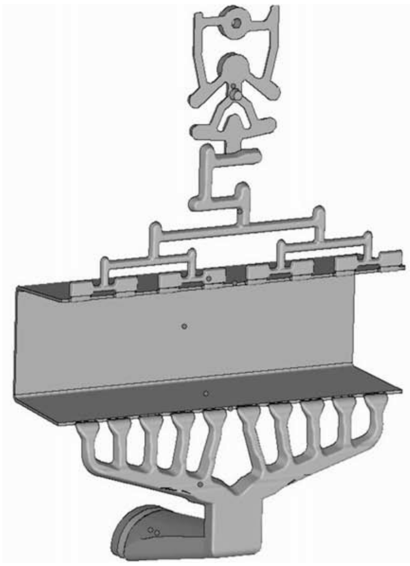

Fig. 1 The multi-gated die, producing a 'U' shaped profile used in this study. Thickness of U-profile: ~2 mm, Length: ~300 mm, Width:~90 mm, Height: ~75 mm. Total casting: ~1300 g

In order to examine the gate microstructure, both longitudinal and transverse sections of the gates were investigated. Longitudinal sections spanned the runner-gate-casting junction. Transverse sections were taken from a plane in or near the gate with the filling direction perpendicular to the section. Sections were mounted in Bakelite and prepared using standard metallographic methods. OPS was used as a final step to finely polish and mildly etch the microstructure for examination of the primary Al and eutectic. Samples were then etched using a solution of (60ml H_2O + 10g NaOH + 5g $K_3Fe(CN)_6$) for ~10s to investigate macrosegregation features.

3. Results and Discussion

Figs. 2(a)-(d) show the typical microstructural features in the gates, taken from longitudinal sections of the casting. The gate microstructures contain similar features to previously reported hypoeutectic Al-Si-based HPDC components [7, 10]. For example, this AlSi9MgMn casting consists of 10-30μm equiaxed α-Al grains with rosette-like morphology in a matrix of Al-Si eutectic with a fine eutectic spacing (Figs. 2(a) and (b)). Past research using a different die quantified the Sr-modified HPDC Al-Si eutectic spacing as being 350 ±50 nm [10]. Measurements taken from SEM images of transverse samples indicate a eutectic spacing of 670 ±25 nm in this casting. The small grain size and fine eutectic spacing are closely related to the high cooling rate of 10^3-10^2 K s^{-1} in the die cavity [11], and the combination of high cooling-rate and highly-turbulent filling lead to the rosette-like α-Al morphology. In addition to the fine in-cavity solidified α-Al grains, the gates also contain a small population of significantly larger externally solidified crystals (ESCs), such as that in Fig. 2(c), that nucleated in the shot chamber, where they grew under a relatively low cooling rate, before being transported into the die cavity during filling [8, 12, 13]. The microstructures also contain dispersed α-type $Al_x(Mn,Fe)_ySi_z$ intermetallics due to impurity Fe and the addition of Mn. In Figs. 2(a) and (b), intermetallics are indicated with arrows and are shown at higher magnification in Fig. 2(d). These microstructural features and their length scale were not significantly different in the gate when compared to the main casting.

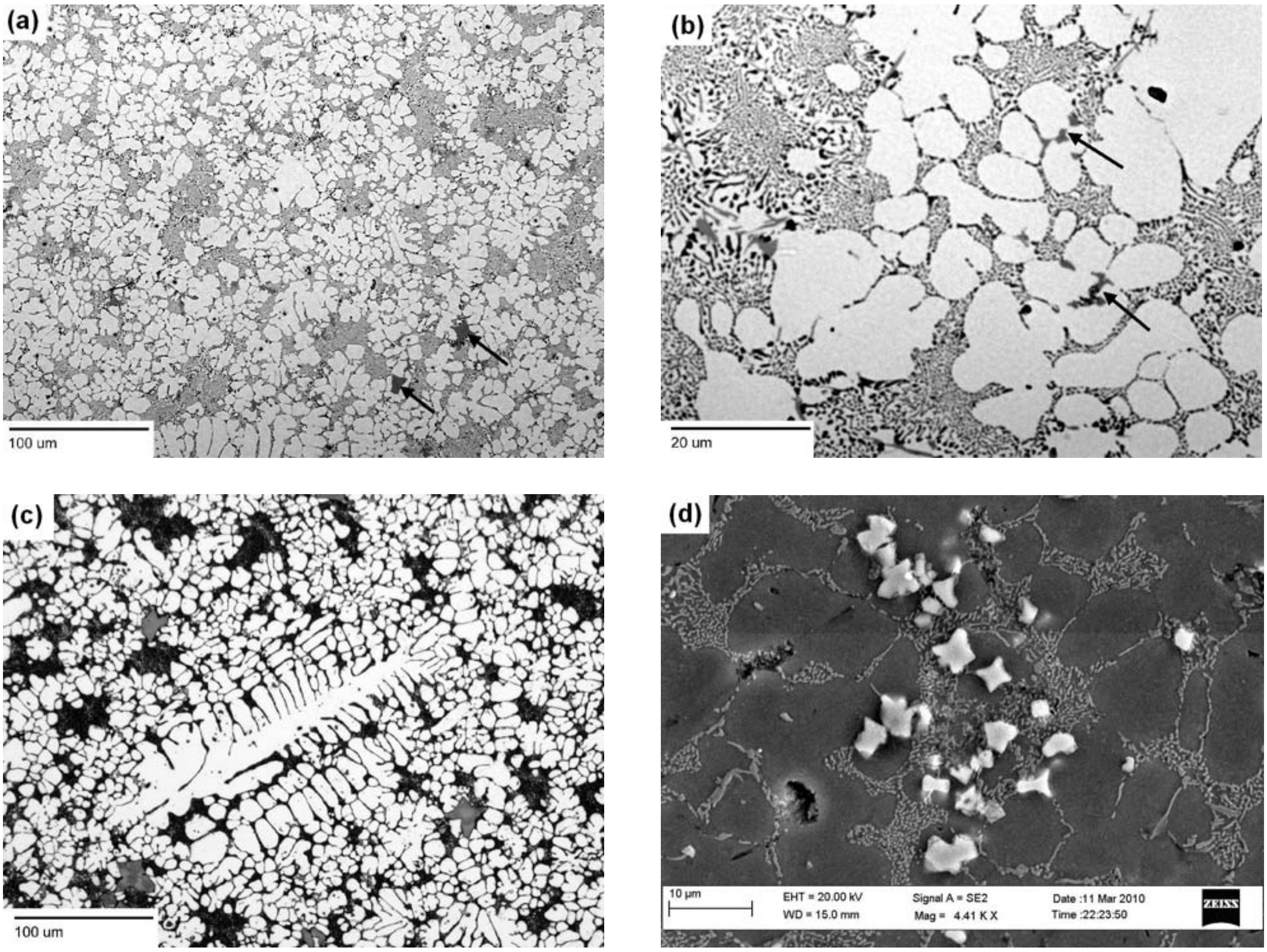

Fig. 2. (a) Typical gate microstructure containing primary α-Al, Al+Si eutectic and intermetallics. (b) Higher magnification showing fine eutectic structure between primary α-Al. Arrows in (a) and (b) indicate intermetallics. (c) A large dendritic ESC after etching. (d) Secondary electron SEM image of α-type $Al_x(Mn,Fe)_ySi_z$ intermetallics (bright).

Fig. 3 shows typical macrostructures of the gate region, where Fig. 3(a) is the runner-gate-casting junction with filling from left to right, and Fig. 3(b) is a transverse section from the location marked by a white arrow in Fig. 3(a). The microstructure is not homogeneous across either section. At the runner-gate-casting junction (Fig. 3a), two dark bands can be seen emanating from the relatively thin gate into the casting. After a small region of band divergence, the bands run parallel to the casting surface. In the transverse section just ahead of the gate (Fig. 3b), these bands form an annulus of darker material. Black arrows indicate bands in Figs. 3(a) and (b)

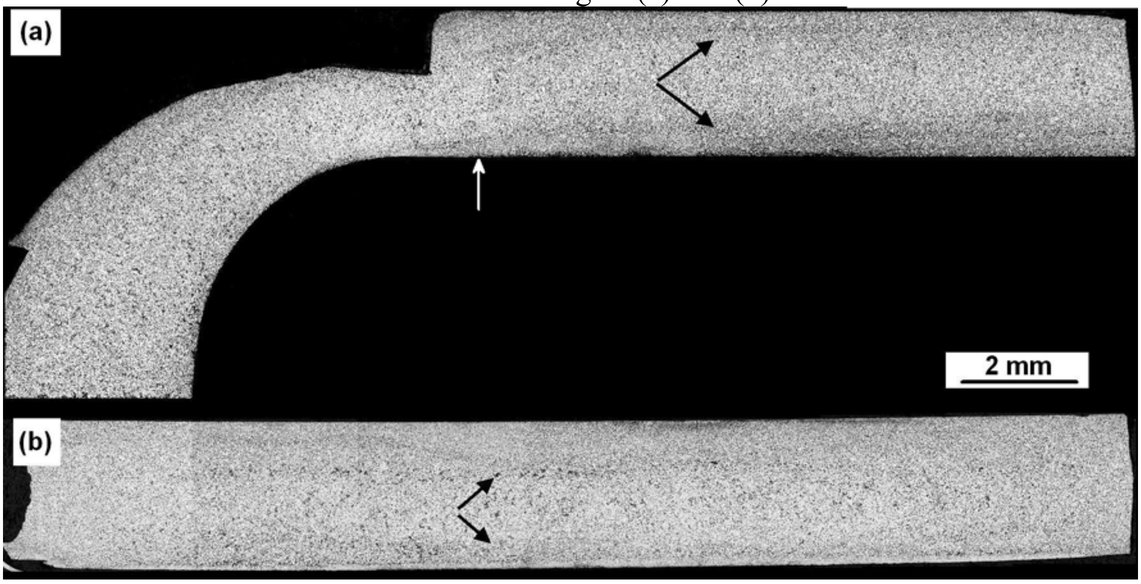

Fig. 3 Gate macrostructures. (a) longitudinal section of the runner-gate-casting junction where filling was from left to right. (b) transverse section just ahead of the gate (marked by white line in (a)) where filling was into the page. Black arrows mark bands of positive macrosegregation.

Fig. 4 shows the macrosegregation profile across the casting thickness close to the gate. Data was obtained by measuring the mean eutectic fraction at 220μm intervals by approximating the eutectic fraction as the fraction of black in etched micrographs. The data should be interpreted in terms of relative changes in the eutectic fraction because the measurement method ignores the presence of intermetallics, and etching can alter the apparent fraction of α-Al. Similar to HPDC research using different Al-alloys in different die geometries [6, 10], there are three dominant macrosegregation features in Fig. 4. First, there is a general increase in the eutectic fraction from the casting centre to the surface; second, there is a localized positive segregation distribution coinciding with the dark bands in Fig. 3a; and, third, there is a surface region of high eutectic fraction.

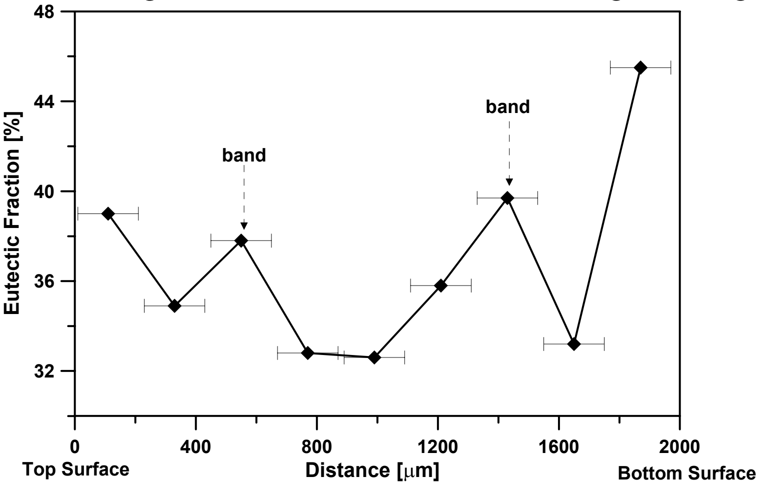

Fig. 4: Macrosegregation profile across the longitudinal section near to the gate. The locations of the dark bands in Fig. 3a are indicated. “Error bars“ show the region of measurement.

Figs. 5a-c confirm that the dark bands contain a higher fraction of Al-Si eutectic than the surroundings. The bands have characteristics consistent with the HPDC defect bands widely reported in the literature [6-8] and the semi-solid shear bands created in laboratory rheology studies [6, 14]. For example, the band thickness is in the range of 6-18 mean grains thick (Fig. 5a) and the bands do not contain a significant porosity fraction, consistent with past work on HPDC Al-alloys [6, 7, 10], and unlike the porosity bands common in Mg-alloy HPDC parts [6, 15]. This indicates that the dark bands are the result of semi-solid shear banding.

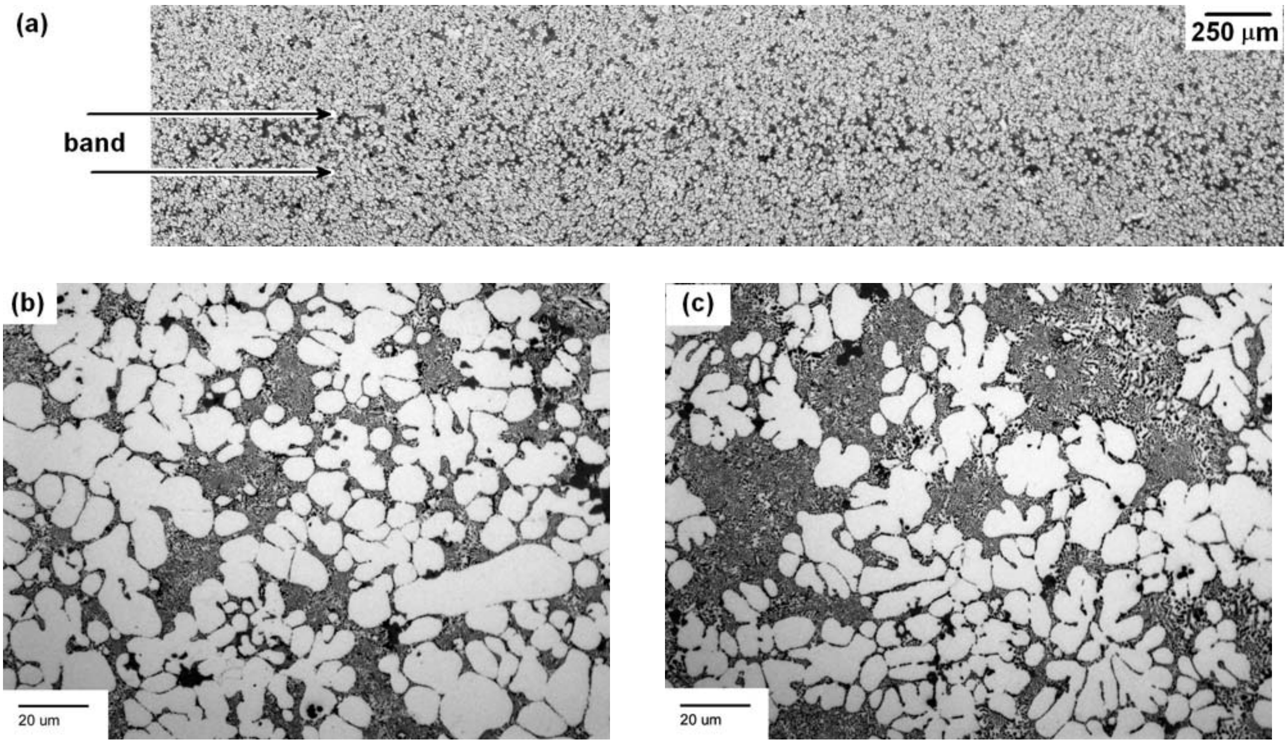

Fig. 5. Typical segregation band microstructure. (a) the band region from Fig. 3a at higher magnification. (b) away from the band; (c) in the band.

The segregation bands appear to begin in the runners and become distinct as they approach the runner-gate-casting junction. By ~2mm before the junction, segregation bands are clear in Fig. 3(a) and run through the relatively thin gate into the casting. This observation is similar to previous work where defect bands emanated from the runners into the casting [5] when sufficient intensification pressure (IP) was applied.

The occurrence of shear banding through the gate only when sufficient IP is applied [5] suggests that shear banding through the gate occurs during the IP stage and that strain localisation can assist in feeding the casting by creating weak shear zones that reduce the barrier to transporting material into the cavity in the latter stages of HPDC. The present study used an IP value that was optimised for this die, and shear banding was observed through the gates, suggesting that similar feeding mechanisms operate in the current case.

Comparing the observations in this and the previous study, shows that shear banding through the gate at optimized IP levels occurs when using (i) markedly different die geometries (a single gated die with a large casting to gate thickness ratio in [5] vs. the multi-gated die with a small casting to gate thickness ratio here), and (ii) different alloy compositions (AlSi3MgMn in [5] vs. AlSi9MgMn here). This result suggests that shear banding through the gate during the IP stage is most likely a general HPDC phenomenon and not a strong function of the die and alloy used.

Conclusions

The gate microstructure of an AlSi9MgMn HPDC casting has been characterised to quantify the key microstructural features and investigate whether semi-solid shear banding occurred through the gate. The general microstructural features in the gate were similar to the main casting. In particular:

- two α-Al grain populations were present corresponding to in-cavity solidified grains (10-30μm) and externally solidified crystals (~>50μm), originating from the shot chamber.
- the α-Al was surrounded by a matrix of fine Al-Si eutectic, with a spacing of 675 ±25 nm.
- dispersed α-type $Al_x(Mn,Fe)_ySi_z$ intermetallics were present due to impurity Fe and the addition of Mn.

Bands of positive macrosegregation with the characteristics of dilatant shear bands were present in the runner, through the gate and into the casting, suggesting that semi-solid shear banding occurred through the gate. This observation is similar to that made previously in a markedly different die using AlSi3MgMn. This suggests that semi-solid shear banding through the gates during the intensification stage is most likely a general feature in Al-alloy HPDC.

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