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Filling, Feeding and Defect Formation of Thick-Walled AlSi7Mg0.3 Semi-Solid Castings

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Abstract. Aluminium semi-solid castings have gained increased attention due to their superior mechanical properties, lower porosity compared to conventional high pressure die cast material. These characteristics suggest that semi-solid casting should be suitable to produce thick-walled structural components, yet most successful applications of semisolid casting have been for thin-walled components. There is a lack of understanding on filling and feeding related defect formation for thick-walled semi-solid castings. This study aims to fill this gap. In the current study an AlSi7Mg0.3 aluminium alloy was used to produce semi-solid castings with a wall thickness of 10mm using a Vertical High Pressure Die Casting machine. The RheoMetalTM process was used for slurry preparation. The primary solid α -Al fraction in the slurry was varied together with die temperature. The evaluation of the filling related events was made through interrupted shots, stopping the plunger at different positions. Microscopy of full castings and interrupted test samples was performed identifying the presence of surface liquid segregation, shear bands, gas entrapment, shrinkage porosity as well as burst feeding.

Introduction

Semi-solid metal processing (SSM) presents a set of advantages over traditional High Pressure Die Casting (HPDC) method. The production of components with lower shrinkage and gas porosity defects due to the associated laminar flow [1] and longer die life [2] are key advantages associated to this casting process. The production of thick-walled structural components may retrieve benefits of this production process due to its intrinsic characteristics.

RheometalTM slurry preparation process described in [3] is very effective, enabling the production of a slurry within 30 seconds and can be included in a HPDC line without many changes or investments, which makes the process very attractive for industrials. Although, the solid fraction obtained by this process is much higher than the predicted from lever rule or Scheil equation [4] and difficult to control, giving space for a large scattering [3].

There is a lack of information in literature regarding the filling and feeding behavior of semi-solid thick-walled castings, which present a great influence in defects level and consequently fatigue response of components. Presence of surface liquid segregation [5-8], shear bands [9], entrapment gas, shrinkage porosity and burst feeding will strongly influence their properties [10] and it is important to understand the influence of process parameters such as die temperature and primary α -Al solid fraction in further casting soundness. Microstructure heterogeneity is typical in SSM due to the separation of pre-solidified particles and liquid during cavity filling [11], giving space to segregation happen and understand the influence of the different parameters is imperative.

Lauki, H. I., et. al. [12] studied the migration of the externally solidified crystals (ESCs) formed in the shot sleeve previous to the injection of the metal in die cavity in HPDC. They have noticed that the ESCs position during die filling is affected by die temperature and solid fraction, with the tendency to concentrate in centre for low solid fractions and low die temperature and be more distributed through the cross section for high solid fractions and high die temperature.

Dahle, A. and StJohn [13] have presented a framework which relate defect formation to the coherency and packing point of partially solidified slurries, when shear is applied. Feeding mechanisms are also included. They have claimed that the solidification of an alloy is divided in three different regions, depending on the coherency point is achieved (point at which the primary particles start to restraining each other movements and to move particles need to deviate others from their path, increasing the space between them which is filled by liquid, base of dilatancy shear bands formation) or packing point, where different feeding mechanisms are associated. For primary α -Al solid fraction lower than the coherency point the material behaves as a liquid and mass feeding is prevalent. After the coherency point and before the packing point, where the resistance to flow is relatively low and flow occur in liquid films (shear bands), the feeding mechanisms associated to this region were mass feeding and interdendritic feeding. After the packing point, third region, the stress associated to shear increase sharply until the metal meets the strength of the solid. When high loads are applied to promote shear, fracture of the solid network may happen, resulting in cracks or porosity when no time is available to fill the formed voids with liquid. In other hand, if feeding is sufficient, large areas of liquid segregation may appear. The feeding mechanisms associated to this third region are interdendritic, burst and solid feedings.

The present work tries to stablish the die temperature and primary α -Al solid fraction influence on filling and feeding behaviour of SSM thick-walled castings.

Experimental

Slurry preparation. The RheoMetalTM process was used for slurry preparation, with the stirring rate and melt temperature kept constant in all experiments, around 800rpm and 650°C (35°C of superheat) respectively. The primary α -Al solid fraction of the slurry was varied by the Enthalphy Exchange Material (EEM) amount added to the melt with 6, 7, 8 and 9%wt. been used. The EEM were preheated up to 200°C before been attached to a rotational engine some seconds before slurry preparation. The slurry preparation time was approximately 18s.

The alloy used in this work was aluminium A356.

Casting Trials. Interrupted and full shots in SSM casting were performed in a 50ton Vertical High Pressure Die Casting machine (VHPDC) machine. For the interrupted shots, the plunger movement was stopped at different lengths of filling, equivalent to begin, middle and end of filling, in order to have approximately and in-situ observation of the metal flow pattern in die cavity. In full shots, the die cavity was completely filled. Plunger speed was kept constant at ~0.4m/s in all experiment. Die temperature was changed by altering the oil temperature which circulate in the die channels and two temperatures were used, 175 and 240°C. From now on, die oil temperature of 175°C will be referred as low die temperature and die oil temperature of 240°C as high die temperature. The top view of the 10mm thickness SSM casting is shown in Figure 1 (a).

Materials Characterization. Optical micrographs were taken from the longitudinal cross-section of the castings, as shown in Figure 1 (b). To analyse the primary α -Al solid fraction, five micrographs of each section identified in Figure 1 (a) (A – Beginning of filling; B- Gauge; C – End of filling) were taken in full castings. For microstructural analyses, micrographs were taken from the longitudinal cross-section at front of filling and beginning of filling in interrupted shot related castings. Particles with area below 1500 μm^2 (~45 μm in diameter) were removed to analyse the α -Al solid fraction due to the fact that particles below this size likely form in die cavity. Image analysis software was used to measure the solid fraction.

Figure 1 – a) casting shape and different zones analyzed in the work, A - Grip Start, B – Gauge and C - Grip End. b) longitudinal cross-section analyzed marked as white.

Results and discussion

In this work, die temperature alteration and %wt. EEM added resulted in different microstructural characteristics observed during filling and feeding. The results in the form of microstructural defect features found are collated in Table 1. Surface liquid segregation (SLS), shear bands, burst feeding and shrinkage porosity bands presence were identified. It is important to point out that Table 1 shows the microstructural features observed in full castings and not during filling. **Figure 2** shows examples of the detected defects.

Figure 2 – a) 1 - SLS, 2 - shear bands observed in 6%wt. EEM full casting. b) 3 – burst feeding, 4 – porosity band observed in 7%wt. EEM full casting. Both results were obtained for high die temperature.

Table 1 – Resume of the microstructural features presented in full castings.

	Die Temperature	SLS	Shear Bands	Burst Feeding	Porosity Band
6%wt. EEM	High	YES	YES	YES	YES
	Low	YES	NO	YES	YES
7%wt. EEM	High	YES	YES	YES	YES
	Low	YES	NO	YES	NO
8%wt. EEM	High	YES	NO	YES	NO
	Low	YES	NO	YES	NO
9%wt. EEM	High	YES	NO	YES	NO
	Low	YES	NO	YES	NO

From Table 1 is possible to observe that shear bands are visible for castings where lower EEM amount were used 6 and 7%wt. EEM and high die temperature. For low die temperature and for 8 and 9%wt. EEM amounts added whatever the die temperature, no shear bands were observed. Hence, the results appears to follow the trend observed before in conventionally HPDC cast Al-Si material, in which higher solid fractions does not promote shear bands formation [14]. However, in this work, the increasing of %wt. EEM amount added did not result in a higher fraction α -Al in the slurry measured along the longitudinal centreline of the castings, Figure 3 (a), where is expected that particles formed during slurry preparation migrate. It seems there is no primary α -Al solid fraction variation with increasing %wt. EEM amount added for low and high die temperature, contrary of expected [3, 15]. The distribution of primary α -Al changes with die temperature and the intrinsic solid fraction [12]. Hence, the measure of solid fraction just in the longitudinal centreline associated to the transversal macrosegregation associated to SSM casting, maybe do not give the entire picture regarding the solid fraction present. Figure 3 (b), shows the primary α -Al solid fraction, with measurements been conducted randomly in all cross-section, retrieved from zones B and C in Figure 1, last zones to be filled in the casting. It seems there are two trends, the primary α -Al solid fraction increase with the increase of %wt. EEM amount for high die temperature and the primary α -Al solid fraction decreases with %wt. EEM amount increase for low die temperature. During pouring step of the partial solidified metal to the shot sleeve, it is clear the increase of melt inhomogeneity with the increase of %wt. EEM amount added during slurry preparation. With

inhomogeneity it is intended the presence of solid clusters within the slurry, likely due to incomplete EEM dissolution during slurry preparation. An indication of this solid clusters existence is shown in Figure 4, marked by a circle, where is visible their dendritic structure typical obtained in EEM. The higher thermal gradient existent between the die walls and melt will introduce a higher flow constraint due to solid formed at die walls [12]. The higher flow constraint (in Figure 4 the flow constraint can be observed by the shift of burst feeding (marked by left and right arrows) to the left due to the higher thermal gradient existent from the upper die wall on the left) linked to the presence of solid clusters, may result in a “sponge effect” when the melt is injected to the die cavity, with the solid clusters been trapped during filling with the lower solid fraction slurry, which offer less resistance to flow, move ahead in the filling front. This would result in a presence of lower solid fraction in the last zones to be filled, with the increase of %wt. EEM amount. The increase of solid fraction with %wt. EEM amount observed for high die temperature could be the result of the more likely presence of higher amount of this clusters in the last zones to be filled. The lower thermal gradient existent between die walls and melt will result in lower flow constraint, consequently less barriers for this solid clusters flow through die cavity.

Figure 3 – a) Primary α -Al solid fraction measured in the longitudinal cross-section centreline and b) primary α -Al solid fraction measured randomly in longitudinal cross-section in zones B and C in Figure 1 (right).

It was expected that for low die temperature, the primary α -Al particles formed during slurry preparation, migrate to the centre result from cold die wall flow constraint [12] and consequently, higher concentration of α -Al particles would be observed in the centreline for low die temperature castings. This trend is slightly observed for the 6%wt EEM but not for higher %wt. EEM amounts as shown in Figure 3 (a).

Although most of features shown in Table 1 were observed in full castings, there were shear bands and burst feeding observed during filling. Hence, the shear bands and burst feeding formation are not exclusively formed in the last stage of SSM casting, during the intensification pressure stage. The reason for the burst feeding observed in Figure 4 during filling can be linked to the presence of the solid cluster, which strongly increase the solid fraction locally enough to reach the packing point and when high loads are present, as in the case, fracture of the solid network happen resulting in cracks and large areas of liquid segregation, pointed with arrows in Figure 4.

Figure 4 – Solid cluster identified by a circle maybe formed during slurry preparation present at beginning of filling for the 8%wt. EEM casting, low die temperature and intermediate length filling.

Figure 5 show the presence of SLS in 7%wt. EEM for high die temperature in interrupted casting (a) and full casting (b). The top of both figures is the casting surface in contact with die wall. It is possible to observe higher fraction of primary α -Al particles (white big near spherical particles in Figure 5) for interrupted filled casting compared with full casting, indication of smaller SLS for interrupted filled casting. The SLS width have big variations along the casting, ranging from around 150 μ m to more than 1000 μ m in the case of the castings in Figure 5. This liquid segregation can be resulted from the combination of two mechanisms, inverse segregation [14] and melt exudation [14, 16]. The inverse segregation is a consequence of the flow of alloying elements rich liquid towards the die wall (heat flow) to compensate the solidification shrinkage happening when the metal contact the die wall [14]. This may be the main mechanism taken place in interrupted castings, where the intensification pressure stage is avoided. Another mechanism that occur in direct chill castings [16] and likely is also active in SSM full castings is referred as exudation. The contraction of the casting leads to an air gap formation between die wall and the solidifying casting, while the semi-solid casting skin is stretched in the end of filling by the intensification pressure, resulting in fracture and small bleeds (circle in Figure 5 (b)) toward the surface, where solute-enriched melt move from the centre to the die wall [16]. The degree of SLS is linked with the intensification pressure degree [14] resulting in the higher SLS observed in full casting microstructure, Figure 5. It is interesting to observe in Figure 5 (b) the presence of both shear bands and burst feeding.

Figure 5 – Micrographs obtained for 7%wt. EEM castings at zone A in Figure 1 for high die temperature at a) intermediate length of filling and b) full casting.

The presence of shear bands was also observed during filling in 6 and 7%wt. EEM and high die temperature castings, meaning that its formation is not exclusive of the intensification pressure.

For lower %wt. EEM amount added and high die temperature, the presence of shear bands adjacent of die walls result in porosity band formation in the voids formed due to burst feeding. As the solidification progress from the die walls toward the centre of casting, the liquid consumed in the shear bands to compensate the shrinkage, will be missed in the voids formed due to burst feeding, creating porosity bands.

Conclusion

The following conclusions can be made:

- For higher %wt. EEM amount added the presence of shear bands was not detected.
- For lower %wt. EEM amount added and high die temperature, the presence of shear bands adjacent of die walls result in porosity band formation in the voids formed due to burst feeding.
- The intensification pressure applied increase the transport of melt towards the die walls, increasing the SLS present at casting surface. When intensification pressure is not applied the SLS formed is much smaller.
- Shear bands and burst feeding formation are not exclusively formed during the intensification phase pressure. Burst feeding was strongly linked to the solid fraction locally and with

sufficiently high solid fraction burst feeding occurs. This strongly stresses the need of preparation a homogeneous slurry to avoid this defect.

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