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Blistering in semi-solid die casting of aluminium alloys and its avoidance

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ABSTRACT

Semi-solid die casting of relatively high solid-fraction aluminum alloys (0.5–0.7 fraction solid) can be used for the production of high quality industrial components. However, surface blistering during solution heat treatment can still be a problem and is associated with the entrapment of gas whether from air or from burned lubricant. Here the mechanism for formation of blisters is presented. The Reynolds number *in the surface layer* of the semi-solid flow is then analysed to obtain the relationships with hydraulic diameter and flow velocity for different slurry temperatures. The hypothesis is that it is some flow instability at the flow front, even where the overall nature of the flow is essentially laminar, which is leading to the entrapment. The crucial finding is that if the Reynolds number is plotted against temperature there is a decrease followed by an increase. The position of this minimum is dependent on the ratio of fill velocity to the hydraulic diameter, v/D. Thus there is a 'sweet spot' in terms of temperature (*i.e.* fraction liquid), flow velocity and hydraulic diameter (*i.e.* die design) where the flow front has the maximum stability, giving maximum resistance to blister formation. This is in contrast with conventional wisdom which would suggest that low fractions liquid would give the most stable flow front. A rationale for this is presented in terms of the particle crowding at the relatively low fraction of liquid.

Experimental results with aluminium alloy 319s as an exemplar, and a die which has varying cross sectional dimensions, are presented and validate the hypothesis.

1. Introduction

Components produced by conventional high pressure die casting (HPDC) are typically not heat treated due to the presence of casting defects such as entrapped air and lubricants that cause surface blistering during solution heat treatment [1]. The gases and lubricants are entrapped beneath the surface of the castings due to the non-planar and turbulent flow conditions during cavity filling, as illustrated by Fig. 1a. Several high integrity die casting processes, *e.g.* high-vacuum die casting, squeeze casting and semi-solid die casting, have been developed to overcome this entrapment problem [2].

Semi-solid die casting is a semi-solid processing (SSP) technique that is gaining increasing industrial application, especially in Asia with light alloys such as aluminium and magnesium [3]. Unlike other casting processes, it does not utilize a fully liquid feed material, but instead uses a material that is partially solid and partially liquid (as reviewed in Ref. [4]). The slurry is injected into a reusable steel die, and once the cavity is fully filled, an intensification pressure is applied as the slurry solidifies, to feed solidification shrinkage. The flow regimes for semi-solid alloys with relatively low solid fractions have been characterized by Janudom et al. [5] based on the ratio of gate speed to initial solid fraction (v_g/f_s). With higher solid fractions ($0.5<f_s<0.7$) the high viscosity feed material exhibits laminar flow with a smooth flow front if the process parameters are carefully controlled (Fig. 1b). Therefore, semi-solid die castings typically contain significantly lower levels of

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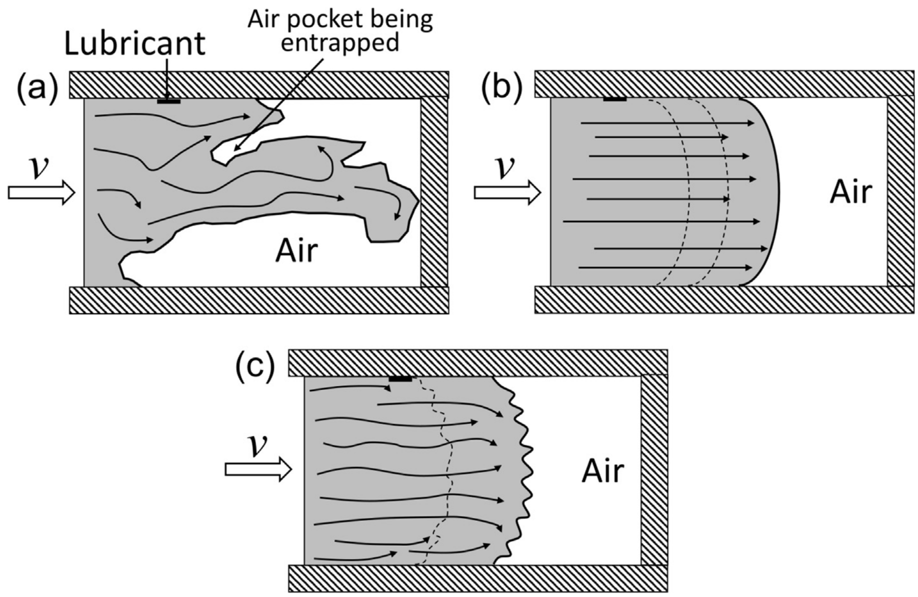

Fig. 1. Graphic illustrations showing different types of flow (a) Non-planar and turbulent flow in conventional high pressure die casting, (b) Planar and laminar flow with high stability in semi-solid processing and (c) Planar and laminar flow with some instability at the semi-solid/gas interface.

entrapped gases and lubricants when compared with conventional HPDC components, allowing them to be heat treated to optimize mechanical properties.

In practice, however, blistering can still be an issue for the commercial production of semi-solid die castings when the process has not been fully optimised [6]. Fig. 1c illustrates the semi-solid flow where there is less flow front stability compared with the flow in Fig. 1b. As a result, some air and lubricants are likely to be entrapped, especially at the locations near the wall. To avoid blistering, commercial aluminium semi-solid castings are often processed using only artificial aging procedures, *i.e.* T5 heat treatment [7], rather than the full solution plus aging treatment, *i.e.* T6 heat treatment [8]. By settling for the T5 procedure, however, one of the major advantages of semi-solid casting processes, namely the ability to generate significantly improved mechanical properties, is not realized. Therefore, it is highly desirable to understand the mechanisms in semi-solid castings, to minimize (or eliminate) blistering during the commercial production of semi-solid castings, thereby broadening the commercial appeal of these types of castings. It should be emphasised that surface blisters occur because of the expansion of gases at high temperature during the solution heat treatment. This process is thought to be the same in both semi-solid and conventional die casting processes, but it is the mechanism of gas entrapment during the die filling process which is significantly different. The level of blistering is determined by the volume and location of the entrapment.

In the present study, the nature of blistering will be examined, the mechanisms of blistering formation during heat treatment will be theoretically analysed, and then factors affecting formation of the blistering will be discussed in term of a 'modified' "Reynolds Number". (The term 'modified' is used here to emphasise that it is the shear rate dependent viscosity which has been used in the formula rather than a constant one). Experimental validation of this theoretical analyses will also be presented, using aluminium alloy 319s as an exemplar. It should be noted that semi-solid die casting practice should ensure that hydrogen contamination is avoided and so it is the entrapment of air/lubricants which is the focus here. The core aim of the paper is assisting with the avoidance of blistering in commercial practice through improved understanding of the control of process parameters.

2. Mechanism of blistering formation

2.1. Nature of blistering in semi-solid die casting

Fig. 2 shows the typical morphology of blisters in a semi-solid casting of 319s alloy. The metal close to the casting surface is plastically deformed by expanding gasses entrapped under the surface of the casting. For the current study, based on the observed locations of gas entrapment that may induce blistering defects, a surface layer with a thickness of one sixth of the hydraulic diameter of the filling channel ($D/6$) is defined (see Fig. 3a). The entrapped gasses can originate from burned die lubricant or from air entrapped during the die filling process and are compressed during pressure intensification. When the casting is later soaked at a high temperature during solution heat treatment, the pressurized gas pockets expand and deform the surface of the casting to form blisters.

Heating or cooling of the casting will change the pressure inside the trapped gas pocket, and the following equation can be used to predict the influence of a change in temperature upon the gas pressure:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \quad (1)$$

where V is the volume of the entrapped gas, T is the absolute temperature, P is the pressure inside the gas pocket, and the subscripts represent different states. Fig. 3 illustrates the detailed mechanism of blistering in terms of three separate stages:

Stage 1: Gas entrapment occurs during die filling if the cavity filling process is not adequately controlled (*i.e.* the flow front is predominantly planar and laminar but with some instability at the semi-solid/gas interface as in Fig. 1c). As illustrated in Fig. 3a, it is possible for the air to be entrapped into the surface layer and then form a gas B (marked in Fig. 3b). The volume of the entrapped gas B is V_1 and the pressure inside the pocket is P_1 at this stage.

Stage 2: After the cavity is completely filled, the intensification