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A new multi-zone model for porosity distribution in Al–Si alloy castings

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Abstract

A new multi-zone model is proposed that explains how porosity forms in various regions of a casting under different conditions and leads to distinct zonal differences in pore shape, size and distribution. This model was developed by considering the effect of cooling rate on solidification and distribution of porosity in Al–Si alloys cast as plates in moulds made with silica, ilmenite or zirconia sand cores or steel chills facing the major plate faces. The alloys cast were Al–7 wt.% Si and Al–12.5 wt.% Si in unmodified and modified forms, the latter with either Na or Sr addition. It is found that, regardless of cooling condition, Si content and modification treatment, the microstructure can be divided into three zones of varying size (across the casting thickness) that are determined by the local cooling conditions and the nucleation and growth mode of the Al–Si eutectic. The zones are: (1) an outer shell-like zone where directional columnar dendritic grains and a fine-celled, coherent eutectic form a low-porosity shell at the casting surface; (2) a transitional zone where equiaxed, eutectic cells grow between columnar dendritic grains and irregular pores become trapped in the mush; and finally (3) a central zone where the thermal gradient is low and equiaxed dendritic grains and eutectic cells grow at the centre of the casting and larger, rounded pores tend to form. The paper discusses how Si content, modification type and cooling conditions influence the location and size (i.e. depth) of each of these zones and how the distribution of porosity is thus affected.

Keywords: Al–Si alloys; Eutectic solidification; Heat flow and solidification; Microstructure; Porosity

1. Introduction

The location, type and size of pores formed in castings are critical for subsequent applications in various ways. Subsurface pores are exposed by machining and affect aesthetic appearance, the presence of large pores at stressed areas detrimentally affect fatigue life [1], and interconnected porosity has an adverse effect on pressure tightness. Numerical modelling of solidification has been reasonably effective in predicting the likely location of significant porosity/shrinkage in castings, but the finer details are still lacking. A more precise mechanistic description to assist with modelling is required.

The formation of casting porosity is known to be significantly influenced by the growth morphology of the solidifying alloy, and in particular the feeding of liquid through the semisolid mush [2]. It is therefore important to understand the operative growth morphologies in order to understand pore formation. It is generally accepted that castings contain three macrostructural zones based on the primary grain structure: a thin and densely packed chill zone at the surface, followed by a columnar zone with directional grains, and an equiaxed zone in the centre [3]. These three regions are not all necessarily observed in any one casting, their actual occurrence being dependent upon alloy composition, solidification conditions and the addition of grain refiner. Of particular importance, however, is the columnar-to-equiaxed transition (CET), which has been considered by many authors [3–7] and is attributed to changes in the spatial temperature gradient,

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local cooling rate and nucleation density in the melt. A similar transition is found in eutectics [8].

In Al–Si foundry alloys, two major reactions occur, one being the formation of the primary α-Al phase, the second being the binary Al–Si eutectic. A series of more complex minor reactions may also occur with increasing complexity of the alloy chemistry. Even in a binary alloy this complicates feeding as the growth modes of both the α-Al phase and the eutectic need to be taken into account. Complicating matters further is the common practice of adding Na or Sr modifiers during the production of hypoeutectic and eutectic Al–Si alloy castings to alter the morphology of the eutectic silicon so that it becomes fibrous rather than acicular, thus improving the alloy's mechanical properties, particularly its ductility [2].

The position and amount of porosity is known to be affected by various factors including the cooling conditions, particularly its directionality, the amount and morphology of the primary phase and the type of modification used. Recent research by Felberbaum and Rappaz [9] has shown that the shape of pores in Al–Si alloys is influenced by the fraction of primary dendrites and the dendrite arm spacing. They also concluded that the gas content in the melt has a major influence on the shape of the pores.

In recent years it has been shown that modification not only changes the morphology of the eutectic silicon but also changes the mode of eutectic solidification [10–15]. Both Sr and Na lower the temperature at which the eutectic grows. Addition of Na forces the eutectic to grow at an almost constant, low undercooling which leads to the formation of a fine, uniformly structured eutectic [10]. Strontium creates an initial undercooling followed by recalescence during which the growth temperature of the eutectic increases gradually to reach a maximum slightly below the unmodified eutectic growth temperature. Towards the end of solidification, the undercooling increases again as the final melt pools trapped between the eutectic cells[1] solidify [11]. The varying growth conditions arising from Sr addition create a well-modified eutectic but the scale of the Si particles usually varies in size from fine in the centre to coarser at the edge of the eutectic cells.

It has been shown that both Na and Sr react with P in the liquid such that the population of AlP particles that serve as nuclei for the Si in the eutectic cells is reduced [12,13]. The reduction of available nuclei suppresses formation of the eutectic, and, as a result, the eutectic undercooling and eutectic cell size are both increased.

When there is a sufficient thermal gradient, Na-modified eutectic cells grow with a relatively coherent, planar front [10–14]. This is not the case for Sr-modified eutectic cells: these are large, approximately spherical and well distributed, forming a mushy zone while eutectic solidification takes place [14–17].

A recent investigation by Tiedje et al. [16] has shown that the ability of Al–Si alloys to form a solid shell and subsequently be responsive to feeding depends very much on the method of modification. In that work it was also shown that the shape of the pores formed is determined by the growth of both primary dendritic grains and Al–Si eutectic cells. Upon reflection, it has become evident that the shape, size and distribution of porosity in Al–Si alloys was characteristically different in three regions/zones of the casting: (1) the solid shell at the casting surface; (2) an intermediate region where large eutectic cells grow between more or less columnar dendritic grains; and (3) the centre of the casting where the eutectic cells form between equiaxed dendritic grains.

The present work is a further investigation into the factors that control the formation of these three zones, and how porosity forms within each of them. In particular, the effect of cooling conditions on solidification and porosity formation in Al–Si alloys in unmodified, Na-modified and Sr-modified forms is investigated. This is used to propose a new description of how modification and process conditions influence porosity formation in castings.

2. Experimental procedure

In this work, several castings, each consisting of three plates (120 mm × 160 mm × 15 mm) with individual feeders, were produced using multi-section silica sand moulds. The moulds were designed such that exchangeable cores could be inserted to face each of the large plate faces (120 mm × 160 mm). These face cores were made with either the same silica sand as the rest of the mould parts, or with other materials. To create a range of cooling conditions, exchangeable cores made of zircon sand ($ZrSiO_4$), ilmenite sand ($FeTiO_3$) or of mild steel (hereafter termed "chills") were used. A detailed description of mould design and assembly can be found in Ref. [16].

The cooling ability, β, of a particular mould material, i.e. the mould's ability to extract energy from the casting, can be defined as [2]:

$$\beta = \sqrt{k\rho c_p}, \quad (1)$$

where k, ρ and c_p are thermal conductivity, density and heat capacity of the mould material, respectively.

For the plates cast between the steel chills heat flow is also controlled by the heat transfer coefficient between the casting and chill. The cooling ability as described in Eq. (1) is therefore not fully sufficient to describe the mould material's influence on cooling conditions but gives a good approximation of how cooling conditions change when mould materials are changed [2].

[1] To avoid confusion, in this paper, the term "cell" (cell size, cell shape/morphology, etc.) will be exclusively used to describe a discrete entity of Al–Si eutectic, i.e. the related Al and Si components, formed from a unique eutectic nucleation event. The term "grain" (grain size, grain shape/morphology, etc.) will be used exclusively to describe a discrete entity of primary α-Al phase, i.e. dendritic or globular-like, equiaxed or columnar in form, formed from a unique nucleation event.