Acta Materialia 127 (2017) 277–286

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Solidification modelling for coupling prediction of porosity and segregation

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ARTICLE INFO

Article history:
Received 28 August 2016
Received in revised form
21 January 2017
Accepted 21 January 2017
Available online 30 January 2017

Keywords:
Al-Cu alloys
Solidification shrinkage
Hydrogen
Porosity
Segregation

ABSTRACT

Porosity is a common casting defect induced by solidification shrinkage as well as gas segregation, nevertheless, it may exert a beneficial effect on reducing alloying element segregation. Unfortunately, the influence of porosity formation on alloying elements segregation in casting alloys have not been synthetically investigated by neither experiment nor theoretical analysis. In this regards, here a theoretical model, based on analyses of the redistribution behaviours of both gas element and the alloying elements, is proposed to simultaneously predict the porosity and segregation in as-solidified Al-based alloys. First, Al-4.5 wt pct Cu alloy with a columnar dendritic interface is selected to mathematically predict the porosity forming process. The modelling results show the same tendency with Poirier's prediction, but the volume percentage of porosity calculated by the present model is lower than that of Poirier's. Besides, the present model predicts a decrease in porosity fraction at late stage of solidification, and more than the previous studies, the gas escaped from eutectic liquid is also evaluated. Then, the impact of porosity formation on the velocity of interdendritic feeding flow is estimated, the porosity in the mushy zone apparently slow down the suction of interdendritic liquid. Finally, a mathematical model for element segregation is derived with consideration of porosity formation. Numerical results show that the solute enrichment in interdendritic liquid gets relieved slightly with porosity formation. Consequently, porosity will reduce the solute segregation.

1. Introduction

Solidification of metallic alloys usually suffers 1%–7% shrinkage. For the shape casting or ingot casting, the macro scale shrinkage is restricted by the mould. Therefore, the solidification shrinkage will take place dispersedly and gradually in a broad region of liquid-solid mixture, namely mushy zone, where the solid fraction increases gradually in the dendrite morphology with the cooling process from the casting surface to the centre until the melt is completely consumed. With the progress of solidification, two coupling phenomena may happen in the mushy zone. First, the solidification shrinkage can be also filled with gas phase, through which the pores will be formed. Secondly, the solidification shrinkage in the mushy zone will drive the solute enriched interdendritic liquid to flow from the high liquid fraction region to the high solid fraction region to compensate the shrinkage. Taking Al-Cu alloys as an example, the interdendritic flow will result in a higher average Cu content in the prior solidified region, through which the so-called inverse segregation [1–3] will be formed. The formation of segregation and pores in the casting is a coupling process and they certainly affect each other. The formation of the gas phase in the mushy zone will squeeze the solute enriched liquid from the mushy zone to the melt, which may reduce the inverse segregation or even cause an opposite solute distribution known as normal segregation.

Simultaneous experimental studies on the formation of segregation and porosity have been done for Al-Cu alloys by Boeira et al. [1], Magnesium alloy by Lee et al. [2], and super alloys by Whitesell et al. [3]. However, theoretical modelling usually treats porosity and segregation separately. Numerical works have been done to predict the porosity in the solidification processing by analysing the liquid feeding conditions in the mushy zone [4–8]. The segregation analyse is normally started from the so-called local solute redistribution equation, which was proposed by Flemings and co-workers [9–11] in the form

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http://dx.doi.org/10.1016/j.actamat.2017.01.042
1359-6454/

$$\frac{\partial f_l}{\partial c_l} = -\frac{1-\beta}{1-k}\left(1-\frac{\vec{V}\bullet\nabla T}{\dot{T}}\right)\frac{f_l}{c_l} \quad (1)$$

where c_l is the solute concentration, f_l is the volume fraction of liquid in the mushy zone, β is the solidification shrinkage, k is the solute partition coefficient at the growth interface, $\dot{T}$ is the cooling rate, ∇T is the temperature gradient, $\vec{V}$ is the liquid flowing velocity driven by buoyancy force.

By solving Eq. (1) under different conditions [1,12,13] or numerical calculation [14,15], the segregation behaviour can be calculated.

In the present paper, a theoretical model for simultaneous prediction of the segregation and porosity is established, based on the analysis on the redistribution behaviours of both gas element and the alloying elements during the solidification. In this model, the porosity is first predicted. And then, the model for the segregation will be developed with consideration of the effects of the porosity. By taking Al-4.5%wt Cu alloy as an example, schematics of formation process of porosity together with solute segregation are shown in Fig. 1.

2. Mathematical models

2.1. Model for the porosity prediction

The formation of pores in the melt or interdendritic liquid in the mushy zone is actually a gas bubble formation process, where the pores are occupied by the gas element dissolved in the melt. The typical gas element dissolved in aluminium alloys is hydrogen, which exhibits high solubility in the melt at high temperature, but it decreases with decreasing temperature and reduces sharply when the melt solidifies due to very limited solubility in the solid phase. Therefore, in the cooling down or solidification process, the dissolved gas element will be supersaturated, which offers a driving force for the gas bubble formation. The driving force can be quantified by the supersaturation pressure P_g,

$$P_g = P_i - P_{ie} = K(c_l(g) - c_{le}(g)) \quad (2)$$

where P_i is the real pressure and P_{ie} is the equilibrium pressure of gas element, equivalent to the gas content in the melt. K is the equilibrium constant, $c_l(g)$ is the real gas element content in the melt, and $c_{le}(g)$ is the equilibrium gas element content in the melt.

Gas bubbles usually nucleate heterogeneously at the root of secondary dendrite arms [6]. Gases ejected from the coarsening arms diffuse into pores continuously, which makes the bubbles growing until they impinge the surrounding dendrite arms. Attributes to the constrained effect of dendrite arms, the pressure in bubbles rises and accumulates gradually to a critical level. Then bubbles jump into the interdendritic space between primary dendrites, they occupy the interdendritic spaces. Their shape follows the surrounding dendrites. Buoyant and convective forces promote this detachment [6]. The nucleation and propagation process of pores indicate that bubbles' radius of curvature should be treated as a function of secondary and primary dendrite arm spacing, respectively. To simplify the model, it is assumed that gas bubbles occur in the space between primary dendrites after nucleation, and they stay in their original position during growth. Thus the radii of the bubbles are only determined by the groove of interdendritic space.

In a study of columnar dendritic microstructures, Jacobi [16] concluded that the primary dendrite arms almost invariably align themselves in an interlocking way, and bubbles fit in the interdendritic space with the principal radii curvature of

$$r = f_l\lambda_1/4 \quad (3)$$

where f_l and λ_1 are the volume fraction of liquid and primary dendrite arm spacing, respectively.

In addition to the driving force of gas supersaturation, the formation of bubbles may be suppressed by other factors, including the atmosphere pressure applied on the melt surface, P_{atm}, the metallostatic pressure which dependent on the depth of the melt in the mould, P_{st}, the pressure of surface tension P_σ, as shown in Fig. 2.

In the mushy zone, the resistance of the dendrite frame to the melt feeding, namely, the pressure drop associated with solidification shrinkage, P_{shr}, will provide a driving force for gas bubble formation [17]. The accumulation of pressure drop due to shrinkage from dendrite tip (where $f_l = 1$) to the mushy zone can be obtained using Darcy's law with Carman-Kozeny approximation [6,18,19]. According to RDG model, the tensile deformation applied on the solid network plays an important role in pressure depression in mushy zone. This contribution, P_ε, is originally attributed to the thermal contraction of surrounding solid frame, where the strain rate can be approximated by $\dot{\varepsilon}\approx\alpha\dot{T}$, where α is the thermal

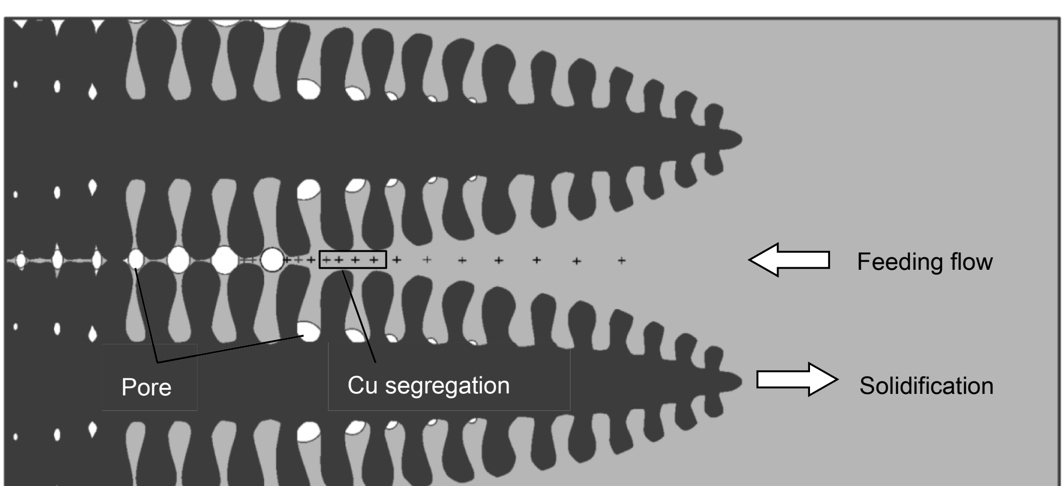

Fig. 1. Schematics of porosity formation and Cu enrichment in interdendritic liquid in unidirectional solidification of Al-Cu alloy with columnar dendritic interface.