



Bond number effects on pore shape in solid



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ABSTRACT

The pore shape affected by Bond number, indicating the ratio between hydrostatic pressure and capillary pressure, of a bubble entrapped by a solidification front is predicted. Bond number is responsible for bubble nucleation, surface area and shape of the bubble or pore cap beyond the solidification front. Surface area determines solute transport across the cap, whereas contact angle of the cap delineates pore shape in solid. The critical velocity for entrapment of a bubble is also related to Bond number. Pore formation in solid influence not only microstructure of materials, but also contemporary issues of biology, engineering, foods, geophysics and climate change, etc. This work extends previous models accounting for mass and momentum transport of solute across a coupled shape of the bubble cap to predict the pore shape in solid. The study also accounts for different directions and magnitudes of solute transport across the cap in different cases. Case 1 is subject to solute transport from the pore across an emerged cap in a concentration boundary layer on the solidification front to surrounding liquid in the early stage. Case 2 indicates solute transport across a submerged cap in a concentration boundary layer to the pore. In contrast to Case 2a, pore value expansion in Case 2b exhibits a more important role in solute concentration at the cap than solute transport across the cap in the late stage. The results show that an increase in Bond number decreases pore radius and time for bubble entrapment in Case 1. An isolated pore cannot be formed in Cases 2a and 2b. The predicted growth and entrapment of a tiny bubble as a pore in solid are found to agree with experimental data. A realistic prediction and control of the pore shape in solid via Bond number has therefore been obtained.

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1. Introduction

Porosity is susceptible to stress concentration, degrading the mechanical properties and impeding efficiency or functional properties of products [1–8]. Substances containing a number of pores have characteristics, such as a low density and a large surface area. As a consequence, they can be utilized as lightweight materials, catalysts, electrodes, vibration, acoustic energy absorption, and impact energy absorption materials, scaffold conducive to tissue ingrowth, etc. [8–10]. Porosity of sea ices also influences the surface elevation of ice sheets, resulting in differences in sun albedo, atmospheric heat and mass transfer, brine, and nutrients transport [11,12].

Since gas solubility in solid is usually much less than that in liquid, solute gas is accumulated ahead of the solidification front [13]. Super-saturation thus induces nucleation of bubbles on the

solidification front [14–17]. The emanated gas bubbles may either float away, or remain at the solidification front where they may be trapped in the solid as discrete pores, chains of pores, or gas tubes [18,19]. The bubbles within the liquid are not often captured by the solid [20]. Therefore, bubble nucleation at the solidification front is the necessary condition for bubble entrapment and pore formation in solid. Pore formation therefore can be divided into different stages: nucleation on the solidification front, spherical growth, solidification rate-controlled elongation, disappearance of the bubbles, and formation of the pores in solid [21].

Relative magnitudes between hydrostatic pressure and capillary pressure governed by Bond number on the cap of a bubble play important roles in pore formation in solid. Liquid pressure is identical to hydrostatic pressure, provided that fluid flow is small and the driving force is gravitational force. Increased surface tension also increases free energy barrier for nucleation of a bubble on a solidification front. The critical velocity for entrapment of a bubble by a solidification front is determined by force balance between gravitational force, surface tension and viscous stresses [22]. Pore shapes in higher purity material changed from cylindrical in

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1 g to spherical in low gravity [23]. In welding aluminum-magnesium alloy subject to a microgravity condition [24], pores were distributed uniformly in the weld. Round shaped pores and narrow and long pores are distributed similarly in upper and lower parts of the weld. On the other hand, larger pores in the terrestrial environment are mainly distributed in the upper part and more smaller pores are distributed in the lower part [24]. Round shaped pores are mainly distributed in the upper part. Small round shaped pores and narrow and long pores are distributed in the lower part.

Bond number is also responsible for shape and surface area of the bubble cap. O'Brien [25] applied the singular perturbation method to solve Young-Laplace equation of a bubble on a surface subject to a small Bond number. The shape of the cap can be uniquely determined by specifying Bond number and contact angle or radius of the bubble cap [26]. Solute transport across the cap into the pore therefore can be relevantly determined. Solute gas concentration in the pore can be influenced by either solute gas concentration in the liquid ahead of the solidification or that away from the solidification front. Depending on which is dominant factor affecting pressure in the pore, directions of solute gas transfer across the bubble cap therefore can be different. Case 1 is applicable for the bubble cap which emerges through a thin boundary layer along the solidification front. Solute is not accumulated at the bubble cap, because solute gas can be easily dissolved in gases in the pore in comparison with that in liquid [27,28]. The bubble is also initiated from heterogeneous nucleation due to solute supersaturation. As a consequence, solute gas is transferred from the bubble to liquid in the early stage [29]. Case 2 represents the bubble cap is entirely sucked into thick concentration boundary layer on the solidification front. The concentration boundary layer results from accumulation of rejected solute gas by the solidification front. Solute gas transfer therefore is from the surrounding liquid through bubble cap into pore [28,30–32].

Accurate prediction of the bubble cap shape is also important for the pore shape in solid. Geometrically speaking, the pore shape in solid is delineated by tracing time-dependent contact angle of the cap [12]. Wei et al. [31] extends a previous study [30] to predict a bubble with a deformed cap trapped in solid as a pore during solidification. The shape of the cap is self-consistently determined by satisfying the conservation of solute and momentum transport and physico-chemical equilibrium. The size of the pore was found to be reduced by increasing Bond number. With a small Bond number the cap to a first approximation can be considered to be a spherical cap.

In this work, the shape of a pore resulting from a bubble entrapped by a solidification front for different Bond numbers is predicted. The model accounts for mass and momentum of solute transport in different directions and physico-chemical equilibrium at the cap. Realistic predictions and more ways to control the growth of the pore and its shape are therefore obtained.

2. System model and analysis

A pore in solid, resulting from entrapment of a tiny bubble on a solidification front, is illustrated in Fig. 1(a). Since contact angle is responsible for the pore shape in solid, Young-Laplace equation governing pressure balance between gas, capillary and liquid pressures is required to predict the shape of the bubble or pore cap beyond the solidification front. Solute gas pressure in the pore is determined by solute transport across the cap in different directions and magnitudes, as illustrated in Fig. 1(b) and (c) and discussed previously. The former, Case 1, is referred to solutes transport from the pore across an emerged cap through a concentration boundary layer on the solidification front into surrounding liquid in the early stage, whereas the latter, Case 2, is applicable to solute transport from the concentration boundary layer across a

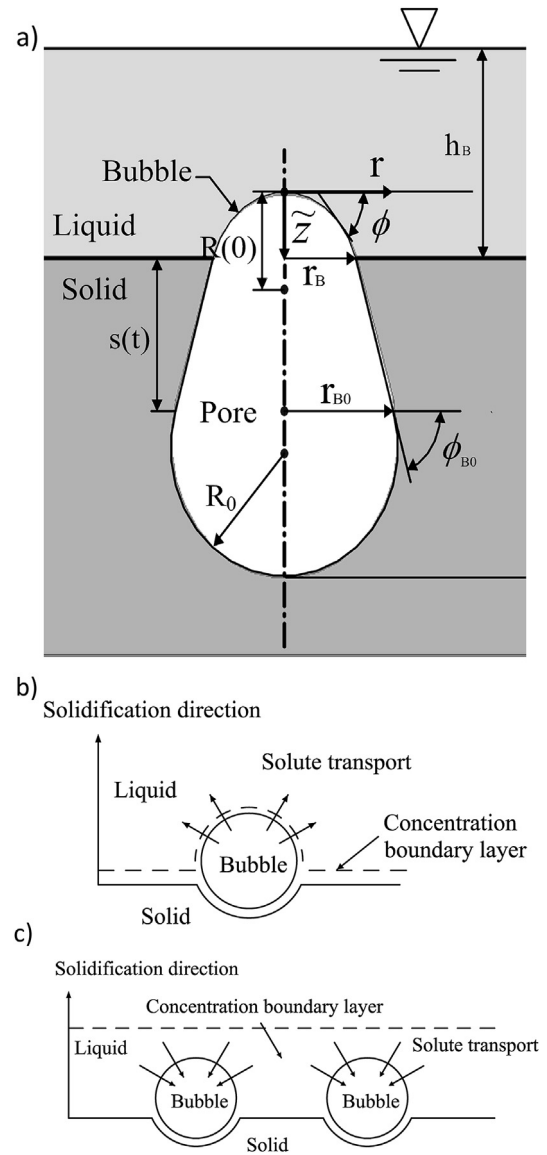


Fig. 1. Schematic sketch of (a) physical model, (b) an emerged cap through a thin concentration boundary layer in Case 1, and (c) a submerged cap in a thick concentration boundary layer in Case 2.

submerged cap into the pore. The major assumptions made are the following:

- 1 The model system is axisymmetric.
- 2 The tiny bubble is defined by a small Bond number, leading to apply available perturbation solutions to predict a lumped micro-bubble in nearly spherical shape. In most cases, Bond number can be as small as 10^{-5} , based on a typical bubble radius of 10^{-5} m during solidification of water.
- 3 The system is static. Tangential and normal viscous stresses in the liquid are therefore neglected. Liquid pressure is hydrostatic pressure.
- 4 Solute transfer across the bubble cap in Case 1 leading to an increase in number of moles of solute gas in the pore is governed by the unsteady differential equation [29].

$$\frac{d\tilde{n}_g}{d\tilde{t}} = \tilde{h}_D \tilde{A}_C (\tilde{C}_\infty - \tilde{C}_C) \quad (1)$$

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