



Effects of mass transfer coefficient on pore shape in solid



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ABSTRACT

The shape of a pore resulting from a nucleated bubble entrapped by a solidification front for different mass transfer coefficients is predicted in this work. Mass transfer coefficient associated with different reference concentrations is used to determine different characteristics of solute transfer rate across the cap of the pore or bubble responsible for the pore shape in solid. Pore formation and its shape in solid influence 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 self-consistently determined shape of the bubble cap whose surface is satisfied by physico-chemical equilibrium beyond the solidification front, to study different mechanisms for pore formation. Mechanism of pore formation can be Case 1, which is subject to solute transport from the pore across an emerged cap through the concentration boundary layer on the solidification front into surrounding liquid in the early stage. Cases 2a and 2b are referred to opposite directions of solute transport across a submerged cap in the concentration boundary layer. In contrast to the former, the latter exhibits stronger effects of pore volume expansion on solute gas pressure in the pore than solute transport. The results show that an increase in mass transfer coefficient decreases pore radius and time for bubble entrapment in Case 1. An isolated pore cannot be found in Cases 2a and 2b, since solute concentration at the cap increases and decreases rapidly in the late stage, respectively. The predicted pore shape in solid agrees with experimental data. Mass transfer coefficient associated with solidification rate can be used to control the pore shape, which strongly depends on directions and magnitudes of solute transport.

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1. Introduction

A study of pore formation in solid is a challenging topic for materials, manufacturing, engineering, biological, geophysics and climate change technologies and sciences [1–12]. Porosity is susceptible to stress concentration, degrading the mechanical properties and impeding efficiency or functional properties of products. Substances containing a number of pores can be utilized as lightweight materials, catalysts, electrodes, vibration, acoustic energy absorption, impact energy absorption materials, food preservation and sterilization, and the scaffold for tissue ingrowth. Porosity of sea ices influences the surface elevation of ice sheets, resulting in differences in sun albedo, atmospheric heat and mass transfer, brine, and nutrients transport [4,13].

Mass transfer across the cap of a bubble or pore beyond a solidification front is responsible for morphologies of the pore in solid [14]. Solute rejected by the solidification front accumulated in liquid near the interface until concentration was high enough for

bubbles to nucleate [15–17]. The growth or shrink of the bubble depends on solute transport across the cap. It has been known that during fast growth there was less time for diffusion and the bubble decreased in cross section. More systematically speaking, enhanced mass transport to the cap from surrounding liquid and gas pressure in the bubble led to a decrease of cap radius in order to satisfy balances of pressures at the cap [18,19]. After nucleation, bubbles experience spherical growth, solidification rate-controlled elongation, disappearance of the bubbles, and formation of the pores in solid [20].

Solute gas transport through the bubble cap can be determined by solving transport equation of concentration in details. Zhdanov et al. [21] numerically calculated a steady-state solute concentration field ahead of the hemispherical portion of a single cylindrical gas bubble entrapped in a growing crystal. Mass transfer across the bubble cap was evaluated by introducing a mass transfer coefficient and a referenced concentration determined by satisfying Young–Laplace equation at the cap with a constant contact angle at each time. Solute concentration decreased along the cap surface toward the axisymmetric axis. Solute concentration increased and decreased in the directions away from the cap. Lotus-type porous metals that contain aligned long columnar pores have recently

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