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Growth kinetics of FeS melt in partially molten peridotite: An analog for core-forming processes

Takashi Yoshino[a,b,*], E. Bruce Watson[a]

[a]*Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy 12180 NY, USA*
[b]*Institute for Study of the Earth's Interior, Okayama University, Tottori 682-0193 Japan*

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Abstract

The growth kinetics of molten FeS pools in partially molten peridotite were investigated by time-series experiments in a piston-cylinder apparatus. The starting materials were mixed powders of peridotite +FeS, with FeS = 6%, 12% and 18% by volume in order to characterize the effect of volume fraction on the growth laws of FeS. The initial particle size of FeS was about 3.5 μm. The samples were annealed at temperatures between 1573 and 1723 K at 1.5 GPa for durations ranging from a few seconds to 100 h. The size of FeS pools was determined by analysis of backscattered electron images. The increase of pool size (G) of FeS with time (t) follows a growth law: $G^n - G_0^n = k \cdot t$ ($k = k_0 \exp(-Q/RT)$). Samples with higher FeS volume fraction have larger pool size at the same conditions. The growth exponent (n) at 1573 K strongly depends on initial volume fraction of FeS and varies between ~2.6 and ~6.4, whereas those at 1723 K are almost constant (~2.3) irrespective of the initial volume fraction. The growth exponent (n) tends to decrease with increasing temperature and volume fraction of silicate melt for each run series of different initial volume fraction of FeS. Low volume fractions of FeS and silicate melt leads to sluggish growth of the pools due to pinning of the silicate mineral phases. The activation enthalpy for pool growth is 331 ± 40 kJ/mol based on the results from samples with 18 vol.% FeS, which show the smallest variation of growth exponent over a range of temperature. These FeS coarsening experiments may serve as tentative analogs for the behavior of a liquid metal phase in hot proto-planetary objects. Assuming exponential heating of such bodies in the early solar system—and allowing for a significant Zener pinning effect of Fe pools—the time spent above the silicate solidus may be insufficient to grow the pools beyond the size where diffusive equilibration with the silicate surroundings can be maintained: in other words, diffusive equilibration may assured because of slow coarsening kinetics.

Keywords: core formation; FeS; growth rate; iron droplet; magma ocean

1. Introduction

Core formation of the Earth and other planetary bodies occurred during accretion by the physical sep-

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* Corresponding author. Institute for Study of the Earth's Interior, Okayama University, Tottori 682-0193 Japan. Tel.: +81 858 43 3734; fax: +81 858 43 3450.
E-mail address: tyoshino@misasa.okayama-u.ac.jp (T. Yoshino).

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aration of metal from silicates. This process is likely to have involved the separation of liquid metal from either liquid or crystalline silicates. The former case would have involved metal-silicate segregation in a magma ocean of the terrestrial planets (e.g. [1]) and the latter case segregation via the grain boundaries of silicate minerals (e.g. [2–4]). If metal segregated by grain edge percolation under hydrostatic conditions, the segregation process would have been inefficient leaving behind about 5 vol.% metal in the silicate due to the high percolation threshold of Fe alloy in silicate matrix [2,3]. Complete segregation of metal from the silicate probably requires substantial or wholesale silicate melting, i.e. a magma ocean. In this case, trapped metal may have been removed from planetary mantles by settling of metal droplets. Therefore, it is important to understand the physical behaviors of sinking liquid metal droplet.

It has been proposed that the high concentrations of moderately siderophile elements (e.g., Ni and Co) in the Earth's mantle are the result of metal-silicate equilibration at the base of a deep magma ocean that formed during Earth's accretion (e.g. [5]). There are two plausible physical models to achieve chemical equilibration between metallic alloy and silicate liquid. One is that equilibration occurs between a layer of metal accumulated at the base of magma ocean and overlying silicate melt and the other is that metal droplets equilibrated with the silicate liquid during gravitational settling. Rubie et al. [6] suggested that since time scales of chemical equilibration are two to three orders of magnitude longer than the time scales of cooling and crystallization of the magma ocean, the concentrations of moderately siderophile elements in the mantle could be the result of chemical interaction between settling metal droplets and silicate liquid in a magma ocean. Knowledge of the iron droplet size is needed to evaluate this model, because the Stokes-law settling speed and the diffusive length scale depend strongly on droplet size. As growing planetary bodies were heated, the metallic particles in undifferentiated materials would have experienced growth before they began to sink by negative buoyancy due to the substantial melting of the silicate. However, growth rates of metallic particles in a silicate matrix have not been determined, and direct experimental determination of the rate laws is needed.

Particle growth under static conditions is a relatively simple transformation in which grain size increases under driving forces arising from surface curvature. The coarsening process of larger particles at the expense of smaller particles is known as Ostwald ripening, and its driving force is the minimization of interfacial energy (e.g. [7]). In the Earth science, most studies of grain growth have focused on silicate, carbonate and accessory minerals (e.g. [8–13]). In contrast, studies of grain growth in partially molten rocks have been comparatively few. Jurewicz and Watson [14] experimentally measured the size of quartz grains in granitic partial melt system as a function of time, and proposed two important processes for the growth rate: Ostwald ripening of crystals in melt and grain coalescence by grain boundary migration. Recently, similar studies have been conducted on quartz in haplograniric melt [15], forsterite in haplobasaltic melt [16], pyroxene in liquid [17] and calcite in partially molten carbonate rocks [18]. However, there have been no studies of particle growth of an immiscible liquid phase in partially molten solids. The growth kinetics of liquid droplet dispersed in a liquid medium with no reacting phase may be different from that in the above case, because the liquid droplets are likely to coalesce with each other and deform easily compared with growing solid particles.

In this study, we investigated the growth kinetics of FeS melt pools in partially molten peridotite to gain a basic understanding of coarsening process of liquid alloy in partially molten silicates. We use our results to consider the question of whether settling iron droplets in a magma ocean could equilibrate chemically with their silicate surroundings—recognizing, of course, that molten FeS is an imperfect analog for liquid Fe–Ni with some dissolved O, S, and other elements. Our results have illustrative value even if the absolute coarsening rates are somewhat different.

2. Experimental procedure

Starting powders were prepared by mixing reagent powder of $Fe_{(1-x)}S$ and spinel lherzolite (KLB1), a fertile spinel lherzolite from Kilbourne's Hole, New Mexico [19]. Because the volume fraction of iron-alloy in the planetesimals is probably less than 20 vol.% based on iron-alloy contents in primitive chon-