

A new constraint for chondrule formation: condition for rapid crystal growth along droplet surface

Hitoshi Miura^{1*}, Etsuro Yokoyama², Ken Nagashima³, Katsuo Tsukamoto¹

¹Tohoku University, ²Gakushuin University, ³Osaka University

Barred-olivine (BO) chondrules are characterized by parallel set(s) of olivine bar crystals, which are platy in three-dimension [1,2]. A BO chondrule usually has an olivine crystal that covers the chondrule surface (rim). The olivine rim has the same crystallographic orientation as the inner olivine platelets. Tsukamoto et al. succeeded to reproduce the rim structure from a forsterite melt droplet in their container-less crystallization experiment using aero-acoustic levitation technique [3]. They found that the droplet cooled very rapidly at a rate of $R_{cool} \sim 100 - 1000 \text{ K s}^{-1}$, and then crystallized within a very short period of time less than $\sim 1 \text{ s}$ at a large supercooling of $DT \sim 600 \text{ K}$. On the other hand, Tsuchiyama et al. also succeeded in reproducing the rim structure by evaporation in vacuum [4]. The cooling rate was $R_{cool} = 1000 \text{ K hr}^{-1}$, which is much slower than [3] by about three orders of magnitudes. Tsuchiyama et al. considered that the rim was formed by the rapid crystal growth along the droplet surface, which should become cooler than the interior by the latent heat of the evaporation. However, their hypothesis has not been verified yet.

To understand the formation mechanism of the rim structure, the crystal growth pattern inside the chondrule melt droplet should be investigated. We carried out numerical simulations of crystallization of a highly-supercooled melt droplet by using a phase-field method [5]. We considered the situation that a tiny crystal seeded at the droplet surface triggers crystallization of the droplet. We found that the rapid crystal growth along the droplet surface occurs when the cooling rate is considerably large. However, they did not investigate for a wide range of the supercooling of the droplet.

In this study, we investigated the condition of the rapid crystal growth along the droplet surface by using the phase-field method. We considered the cases that the seeding occurs when the surface of the droplet is supercooled by $DT_s = 200, 300, 400, 500, \text{ and } 600 \text{ K}$. The surface of the droplet cools at a constant heat flux; $q_s = 5 \times 10^8, 1 \times 10^9, 2 \times 10^9, 5 \times 10^9, \text{ and } 1 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$ for each DT_s . Because of the surface cooling, the droplet surface becomes cooler than the center by $dT_{c-s} \sim 30 - 600 \text{ K}$ for the droplet radius $r_d = 250 \text{ um}$ ($\text{um} = \text{micro-meter}$). We found that the rapid crystal growth along the droplet surface occurred when $dT_{c-s} \sim 100 - 200 \text{ K}$ or larger. The minimum value of dT_{c-s} for the rapid crystal growth along the droplet surface increases as DT_s increases. To derive the minimum value of dT_{c-s} analytically, we compared crystal growth timescales via two different routes inside the droplet; along the droplet surface, and across the droplet center. We found that the growth timescale along the surface becomes shorter than that across the center when $a = dT_{c-s} / DT_s > \sim 0.2$, which condition is rewritten by $R_{cool} > \sim 2000 (DT_s / 300 \text{ K}) (r_d / 250 \text{ um})^{-2} \text{ K s}^{-1}$. This condition is applicable for limited cases that satisfy the following two conditions; (a) crystal growth timescale is much shorter than a cooling timescale of the droplet, and (b) the supercooled droplet is a single component system, namely, the chemical composition of crystal is the same as the parent liquid. If the crystal growth kinetics depends on the growth direction, which usually comes from its crystal structure, we need small modification to the critical values of a and R_{cool} [5]. The new constraint for the rapid crystal growth along the droplet surface is applicable for limited cases, however, this is the first step to understand the formation mechanism of BO chondrule solidification texture.

Reference: [1] Tsuchiyama et al., *J. Geography*, **109**, 845-858, 2000 (in Japanese). [2] Noguchi, *Antarctic Meteorite Research*, **15**, 59-77, 2002. [3] Tsukamoto et al., *Antarct. Meteorites*, **24**, 179-181, 1999. [4] Tsuchiyama et al., *Geochim. Cosmochim. Acta*, **68**, 653-672, 2004. [5] Miura et al., *J. Appl. Phys.*, **108**, 114912, 2010.

Keywords: chondrule, barred olivine, formation condition, crystal growth