Grain growth rates of ice with second phases:Implications for rheology of ice shells an ice mantles in outer solar system bodies

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Various types of icy bodies are present in outer solar system. Differentiated icy bodies are generally composed of icy outer shell, icy mantle and rocky core. Some of them show recent tectonic activities on their surfaces, and some of them show the evidence of existence of liquid-water ocean beneath their icy outer shells. To understand the mechanisms for the presence of such varieties among icy bodies, we should study about thermal convection in icy outer shell and icy mantle that affects their thermal histories and internal dynamics.

Rheology of polycrystalline ice is one of the most important properties controlling the thermal convection. The flow mechanism and viscosity of solid materials strongly depend on the grain size. Therefore in order to understand the convection, we need to know the grain size evolution in icy bodies. One of the important factors controlling the grain size is grain growth process. It is known that the grain growth kinetics of single-phase polycrystal is different from that of two-phase polycrystal.

We carried out grain growth experiments of polycrystalline water ice with the presence of second phase particle such as hydrated sulfate or dust. These second phases have been observed on the surface of icy bodies. We synthesized three kinds of starting materials, pure water ice, water ice + sulfate hydrate ($Na_2SO_410H_2O$), and water ice + dust (soda glass, silica, and alumina), with having uniform grain-size distribution and low porosity. Grain growth experiments were performed using disks (10 mm in diameter and 2 mm thickness) of the starting materials. These disks were kept in low-temperature bath, in which temperature is controlled within 0.2K. Experimental conditions were at 265-272K and 1-72 hours. Microstructures and grain sizes were observed by optical microscope.

The grain growth rate is generally represented by the equation D^2-$D_0{}^n$ = kt, where D is mean grain diameter, D_0 is mean grain diameter at t = 0, k and n are rate constants, and t is time. We have determined grain growth kinetics at 270K. The n-values in the rate equation are 2.9 for pure water ice, 7.7 for water ice + 1 vol.% sulfate hydrate, and 5.5 for water ice + 1 vol.% dust. This suggests that grain growth is significantly inhibited by the presence of small amounts of second phase. Second phase particles appeared to be uniformly distributed. Especially sulfate hydrate exists along grain boundaries of water ice and it appeared to melt once. Dust particles possibly inhibit the grain growth by the Zener pinning force. On the contrary, sulfate hydrate may inhibit the migration of grain boundary not by the pinning, because it does not exist as the particle.

The grain size in icy outer shell and icy mantle is possibly kept small by the presence of second phase as demonstrated in this study. It has been known that the presence of salts or dust in polycrystalline water ice increases the flow strength in the dislocation creep regime. However this becomes effective only when the volume fraction of the second phase is large. On the contrary in the grain-size sensitive creep, the mixing of small amounts of the second phase largely decreases the grain size and viscosity of water ice. This implies that the mixing of second-phase particles makes icy outer shell weaken, which can cause convective instability even in a thin ice shell such as Europa.