Air bubble migration and faceting in ice: X-ray tomography observations vs phase field modeling.

Rémi Granger*[1,2], Christian Geindreau[1], Frédéric Flin[2], Neige Calonne[2], Anne Dufour[2], Bernard Lesaffre[2], Armelle Philip[3], Pascal Hagenmuller[2], Jacques Roulle[2], Laurent Pézard[2], and Sabine Rolland du Roscoat[1]

[1]Univ. Grenoble Alpes, CNRS, Grenoble INP†, 3SR, F-38000 Grenoble, France
[2]Univ. Grenoble Alpes, Université de Toulouse, Météo-France, CNRS, CNRM, Centre d'Etudes de la Neige, 38000 Grenoble
[3]Univ. Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, 38000, Grenoble, France

Keywords: X-ray tomography, ice, crystal growth, cryogenic-cell

Summary: Once deposited on the ground, snow is subject to microstructure transformations that, under some specific conditions, may form faceted crystals. An experiment of air bubble migration in a monocrystalline ice block under temperature gradient monitored with time-lapse X-ray microtomography was performed. This lead to valuable qualitative and quatitative data to evaluate phase-field modeling we recently developped.

INTRODUCTION

Snowpack is a porous media resulting from the accumulation of snowflakes. This is made of ice, air and sometimes liquid water. The complex microstructure, comprising multiple grains with multiple crystal orientations, constantly evolves with time. This result from ice re'distribution by sublimation/condensation and diffusion of water vapor in the pore space. These transformations are called metamorphism of snow. Under important temperature gradient, kinetic forms appear, showing facets. Such facet reveal the expression of the hexagonal crystalline structure of ice and a consequence of anisotropic kinetic coefficent. Modeling metamorphism implies coupling phase change with water vapor diffusion in the air space and heat conduction. Recent developement [1] used phase-field method to solve this problem in weak temperature gradient conditions. In order to improve that model by adding kinetic facetting, we realized time-lapse X-ray tomography observations of an air bubble in a monocrystaline ice block under a temperature gradient. Thanks to the simple geometry of the bubble, this permits a much more controllable experiment while it implies the same physics. Particularly, the use of a monocrystaline ice block of known orientation permits to focus on faceting effects. Observations from this experiment were then compared to phase field simulations with model presented by [1], accounting for kinetic facetting with method presented by [2].

EXPERIMENTAL AND NUMERICAL METHOD

A monocrsytaline ice block was first prepared from liquid water. During freezing, air bubbles forms in the crystal. From the block, a sample was machined and then placed in CellDyM Cryogenic cell [3] for controling thermal conditions on the sample. A temperature gradient of 49 K/m at mean temperature of -4°C was imposed, parallel to the c-axis of the monocrystalline block. The migration has been followed with X-ray microcomputed tomography at 3SR laboratory. 23 acquisitions were performed for 112 h of evolution, with spatial resolution of 7.4 μm. After reconstruction, images were segmented using an interface minimisation method [4]. Evolution of center of mass, volume and inertia matrix of the cavity were then computed on the segmented images.

Finally, finite element simulation were performed with phase-field model with anisotropic kinetic coefficient, varying between $2\ 10^{-6}$ m/s and $2\ 10^{-5}$ m/s.

---

†Institute of Engineering Univ. Grenoble Alpes
*e-mail: remi.granger@3sr-grenoble.fr

RESULTS

A displacement of the cavity occurs, at constant speed of $4.5 \cdot 10^{-10}$ m/s and oriented towards high temperature by sublimation/diffusion/condensation mass transfer. The volume is preserved during the evolution. A basal facet progressively appears on the sublimating side, with slight formation of prismatic facets while the condensing side remains rounded. The measurement of inertia momentums shows a flattening of the cavity. In the phase-field simulation , a facet appears on the sublimating side while the condensing side remains rounded too. The speed of the cavity is constant at $1.9 \cdot 10^{-10}$ m/s. The volume is preserved, and the flattening is also observed although less marked.

References

[1] T.U. Kaempfer and M. Plapp. Phase-field modeling of dry snow metamorphism. Physical Review E, 79, 3,031502, 2009.

[2] T. Uehara and R.F. Sekerka. Phase field simulations of faceted growth for strong anisotropy of kinetic coefficient. Journal of Crystal Growth. 254,1-2, 251–261,2003.

[3] N. Calonne, F. Flin, B. Lesaffre, A. Dufour, J. Roulle, P. Puglièse, A. Philip, F. Lahoucine, S. Rolland du Roscoat, C. Geindreau, J.M. Panel and P. Charrier. CellDyM: A room temperature operating cryogenic cell for in vivo monitoring of dry snow metamorphism by X-ray microtomography. *Geophysical Research Letters, Wiley Online Library*, 42, 10, 3911–3918, 2015.

[4] P. Hagenmuller, G. Chambon, B. Lesaffre, F. Flin and M. Naaim. Energy-based binary segmentation of snow microtomographic images. Journal of Glaciology. 59, 217, 859–873, 2013.

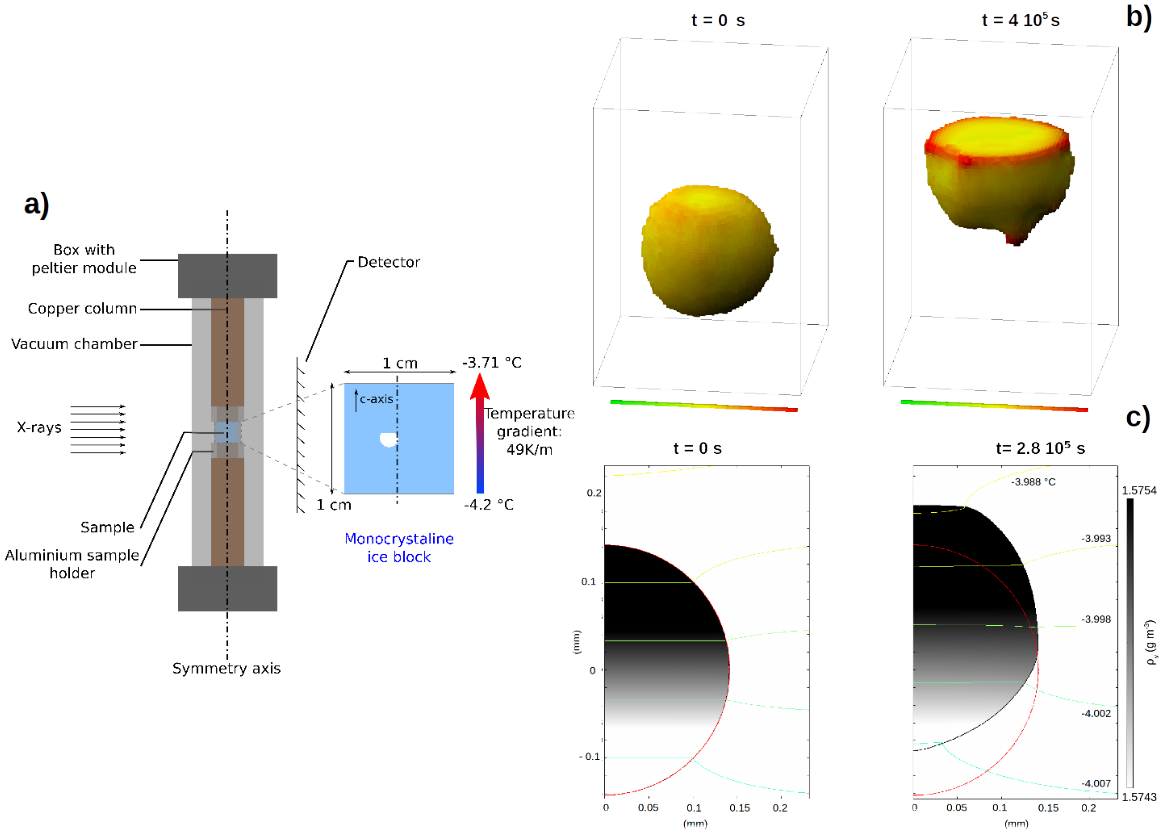

Figure 1: (a) Scheme of the experimental setup. (b) 3D images of the cavity obtained with microtomography, colors represent mean cuvcature of the interface. (c) Simulation results of phase-field modeling. Black and red isolines are interface positions at t = 0 and simulated time respectively. Coloured contours are temperature isolines. Grey levels represent water vapor density in the air space.