FINE STRUCTURE LAYERING IN RADIATION RECRYSTALLIZED SNOW

Edward E. Adams and David J. Walters

Department of Civil Engineering
Montana State University
Bozeman, Montana USA

ABSTRACT: Radiation recrystallization of snow is a near-surface metamorphism process that results in the development of a layer of faceted crystals. When such a layer is subsequently buried by additional snow accumulation a stratigraphic construction that is structurally unstable may result. Previous research has revealed the environmental conditions that result in the formation of radiation recrystallized layers. However, the dynamic process of microstructural recrystallization is not well understood. With the aid of X-ray computed tomography (micro-CT) and optical microscopes, a detailed time history of the recrystallization process has been recorded in sifted, sintered snow subjected to appropriate laboratory-simulated meteorological conditions. Recrystallization has been observed to develop thin layers of unique microstructural morphology within the radiation recrystallized zone. The top surface layer consists of long slender needle crystals connected in a cross-hatch pattern. In addition, a fine layer that consists of small chains of facets oriented parallel to the temperature gradient, which is similar to depth hoar, but on a generally smaller scale, has been identified. Mechanical testing indicates that this weak layer is likely the primary failure stratum. The development of radiation recrystallization is likely the result of vapor flux inducing metamorphism within the snow and deposition at the snow surface.

KEYWORDS: snow, radiation recrystallization, kinetic growth, metamorphism, vapor pressure, gradient

1. INTRODUCTION

Snow is a porous, granular material composed of an aggregate of ice particles bonded together. In the natural environment its microstructure experiences nearly continuous metamorphism. Varying environmental conditions generally lead to the development of a stratified snowpack. One such near-surface layer, which can develop quite rapidly is termed radiation-re-crystallized snow (LaChapelle 1970; LaChapelle & Armstrong 1977; Birkeland 1998; Morstad et al. 2007; McCabe et al. 2008; Slaughter et al. 2009; Slaughter & Adams 2010; Slaughter et al. 2011; Colbeck 1989). This microstructure, when buried by subsequent snowfall, can result in a weak layer, which can be of concern with regard to avalanche stability (Walters et al. 2010; Walters & Adams 2014).

Key to the development of radiation recrystallization is that the radiative absorptivity of ice is wavelength dependent. Broadly speaking, in the visible (short-wave) spectrum ice is quite transparent - although not perfectly so. Radiative energy is absorbed and converted to thermal energy, attenuating with depth. In the infrared (long-wave), it is nearly a black body. Since snow is composed of ice the process of radiation recrystallization is driven its material property. Under clear sky conditions, solar energy induces subsurface heating, while long-wave energy is emitted to the cold sky, cooling the surface. This produces near surface temperature gradients, which can cause near surface metamorphism termed radiation recrystallization.

In this presentation we examine the case of a sample of sifted snow that was allowed to sinter for two weeks prior to being subjected to conditions conducive to radiation recrystallization.

2. METHODS

The procedure was carried out in the Montana State University Subzero Science and Engineering Research Facility. The environmental chamber used for the development of the radiation recrystallization is configured such that the room temperature can be controlled independently from the ceiling. In the center of the ceiling a metal halide luminary provides a simulated solar source to illuminate a sample.

Snow used for the case presented was produced in another cold laboratory, and then stored at -15C

* Corresponding author address:
Edward E. Adams, Department of Civil Engineering, Montana State University, Bozeman, MT 59717; tel: 406-994-6122; fax: 406-994-6105; email: eda@ce.montana.edu
for two weeks prior to subjecting it to conditions conducive to the development of radiation recrystallization (Slaughter et al. 2009).

The initial snow was composed of dendritic crystals sifted through a 0.7 mm mesh into an insulated container 0.7 m x 0.7 m on a side and 0.5 m deep, with an open top. During the sintering phase the top was covered, but it was exposed to the laboratory environment for the radiation recrystallization phase. An X-ray computed tomography (micro-CT) image of the snow sample at the beginning of the radiation phase is displayed in Figure 1.

![Figure 1 CT image of the top 1 cm at the initial stage of the snow sample. The image is of a prismatic rectangular sample with 5 mm x 5 mm cross-section. The orientation of this image is looking at a corner, so that the left and right sides of the image are at the corners and the thinnest part as seen from this perspective.](image)

During the radiation recrystallization phase the container of snow was centered beneath the luminary and cold ceiling. Cold laboratory conditions were held approximately constant for the duration; with a room temperature of -15 C, simulated solar radiation at the snow surface of 706 W m⁻², relative humidity of 70% and calm air conditions.

The concept behind the experimental setup is to mimic natural environmental conditions under which radiation recrystallized snow has been observed to develop. The luminary provides the incident solar radiation source, while the cold ceiling represents the cold clear sky, which affords a radiation coupling between the snow surface temperature and the ceiling.

The example of morphology presented here is part of a series of mechanical tests being carried out on radiation recrystallization metamorphism. In the test presented here shear tests were carried out on similar snow types prior and subsequent to radiation metamorphism in a manner as presented in Walters et al. (2010) and Walters & Adams (2014). In addition and relevant to this presentation, samples of morphology were taken during the metamorphic progression. In an adjacent cold laboratory disaggregated grains were examined under an optical microscope, as would be typical in a field setting. In addition, micro-CT scans were taken that allow for in-situ examination. In this test the morphology was examined at 0, 3, 7, 10 and 12 hours.

3. RESULTS

Starting from an initial essentially isothermal snow temperature, the imposed conditions prompted an alteration of the thermal conditions of the sample. A vertical array of thermocouples was placed in the upper 7 cm of the sample on a 1 cm interval. The surface temperature was measured using a non-contact infrared thermometer. Temperature profile results are presented in Figure 2.

![Figure 2](image)

The influence of the solar warming and long-wave surface cooling is evidenced throughout the profile. At the 3-hour measurement a temperature gradient of 191 C/m was recorded. This transitioned to -5 C cm⁻¹, -110 C cm⁻¹ and -179 C m⁻¹ at hours 6, 10 and 12 respectively. Based on the Clausius-Clapeyron equation calculated for ice over a flat surface the vapor pressure gradient for this final value would be 9 kPa m⁻¹.

In the course of the 12-hour period there was a significant change in the near-surface morphology, which was readily observable. Although there was a significant temperature gradient driving thermal energy from the surface downward during the early stage, no apparent alteration of the snow morphology from the initial form was observed.
Figure 2 Temperature profile variation in the upper 7 cm of the sample over 12 hours; following an initial isothermal temperature of -15 C. The hours coincide with the time of morphology sampling. By 10 hours an average temperature gradient in the top 1 cm of 110 C/m had been established, reaching 179 C/m by the end of the test.

Some evidence of long slender needle-like crystals began to become apparent on the surface by the 7-hour observation (Figure 3). There may have been some grain coarsening just below the surface.

Growth of the surface needles was well developed by hour 10. What also became apparent by this stage was the manifestation of faceted partial cup crystals that had developed just below the needle layer (Figure 4). Distinct hexagonal and rectangular shapes were manifest in these cups. At this time the thickness of the needle layer was ~0.9 mm and the faceted layer ~2 mm. Thicknesses of the individual layers are based on subjective observation of morphology obtained from the micro-CT images. Below this layer the metamorphism was not obvious, although the transition between these layers is not abrupt.

Morphologic evolution continued until the conclusion of the study, at 12 hours (Figure 5). The needle layer developed to a thickness of ~1.25 mm and the faceted cup crystal layer to ~2.5 mm. This faceted cup crystal layer developed columnar structures, with the overall morphology similar that often observed in depth hoar (e.g. Staron et al. 2014). This columnar structure is emphasized in the inset in Figure 5 and in an optical image in Figure 6.

The initial physically measured density of the sample was 155 kg m$^{-3}$. This initial density was synchronized with the CT images and all threshold setting kept the same for subsequent images. Calculations were made of the density through time using micro-CT images for the region in which the cup crystal chains developed. This yielded values of 136 kg m$^{-3}$, 124 kg m$^{-3}$, 114 kg m$^{-3}$ and 126 kg m$^{-3}$. These values are based a small subset of the entire cross-sectional areas.

Figure 3 CT image of a representative sample at hour 7. Orientation and scale is as described in Figure 1.

Another metric that was considered is what is termed the "structure separation" in the Bruker/Skyscan software manual. The parameter is applied to the pore space and represents the diameter of the largest sphere that would be entirely bounded by the pore surfaces. Values calculated in the region in which the faceted cup crystal chains developed were 0.35 mm, 0.37 mm, 0.33 mm, 0.44 mm and 0.52 mm respectively for each of the sampling times.
4. CONCLUSIONS

Results from one laboratory trial on the morpholog-ical development of radiation recrystallization are presented. The example presented here is taken from a study that is aimed primarily at exam-ination of mechanical properties. Results presented for this single trial are representative of the morphologic development observed for all trials in the mechanical study run under similar environmental conditions using comparably produced snow samples, but including different sintering times. A relevant observation from these mechanical tests indicate that failure occurs in the faceted cup chain layer.

It is clear that in the process of radiation recrystal-lization, under at least the prescribed conditions presented, two distinct morphologic structures develop simultaneously. This results in three distinct stratigraphic layers within the top 5 -10 mm of the snow surface, but predominantly in the top 5 mm.

We hypothesize that the two different morphologi-cal developments are both driven by the large temperature gradients. One process occurs due to recrystallization within the snow, the other due to water vapor exiting from the pore space being de-posited onto grains at the snow surface.

The faceted and cup crystal chain growth within the snowcover is driven by mechanisms that de-scribe the development of depth hoar. That is, sublimation from the upper surface of a warmer grain; diffusion of water vapor across the pore and condensation onto the bottom region of a colder grain (Akitaya 1974).

In the second process, large vapor pressure gra-dients will drive vapor from pores that are open to the atmosphere directly from the snow into the overlaying air. This would supply sufficient vapor to be supersaturated relative to surface grains that are cooling through long-wave coupling with the cold sky (ceiling). This process is in agreement with a recent study on the Antarctic plateau by
Gallet et al. (2014) in the growth of what they termed sublimation crystals.

A schematic representation of the presumed simultaneous processes leading to the development of the near surface fine scale stratigraphy due to radiation recrystallization is presented in Figure 7. Hypothesized schematic of the dual processes occurring during radiation recrystallization metamorphism.

Natural snowcovers in general are well stratified. This stratification, which is a response to varying atmospheric forcing, is important with regard to structural integrity. Here we present a particularly fine scale stratigraphic structure that results primarily due to snow and atmosphere radiation exchange. Two distinct morphologic structures are observed to develop simultaneously at the snow surface - atmosphere interface.

Figure 6 Optical images of disaggregated grains illustrating the two morphology structures observed during radiation recrystallization. (a) needle crystals, (b) faceted crystal chain and (c) Both needle and faceted-cup crystals; note that these are disaggregate displays and do not represent natural connection of the crystal types. Grid scale in these images is 1mm.

Figure 7 Hypothesized schematic of the dual processes occurring during radiation recrystallization metamorphism. The red arrow is taken to represent the metamorphism occurring within the snow in a process similar to that which occurs in depth hoar. The green arrow represents the condensation onto the snowcover surface of water vapor that has is source as the snowcover itself.

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REFERENCES


