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Description of the snow microstructure as a 3D assembly of grains

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ABSTRACT:

The concept of snow grain is commonly used in the snow community, either in situ to identify the snow type or in numerical models to reproduce the physical and mechanical behaviour of the snowpack. Among all possible definitions of grains (optical, crystalline and mechanical), we consider mechanical grains as particles separated by potential stress concentrators and mechanical weakness zones. To detect these grains in the snow 3D microstructure captured by X-ray tomography, we use a geometrical algorithm based on curvature and constriction. The algorithm is parameterized with a local contiguity indicator, which defines the segmentation scale. The representation of the microstructure with grains enables the investigation of the bonding system, which is determinant for mechanical properties. In this work, we propose to quantitatively characterise this bonding system with specific grain contact area, contiguity and a new parameter, the minimal cut area defined as the minimal surface of ice separating two opposite faces of a cubic sample. The analysis conducted on 3D images of snow evolving with isothermal metamorphism shows a strengthening of the bonding system, confirming earlier observations on 2D slices of snow. However, the classical description of the bonding system with specific grain contact area and contiguity suffers from a high dependence to the scale of the grain segmentation. On the contrary, the minimal cut area does not depend on the segmentation scale and also measures the connectivity of the bonding system in a given direction.

KEYWORDS: snow, microstructure, grains, segmentation, bonds, mechanics

1 INTRODUCTION

The snow microstructure is traditionally represented as an assembly of grains sintered together. In the field, the snow types are classified according to the grain shapes and sizes within a reference document (Fierz et al. 2009). In models, the microstructure is simplified into individual particles to reproduce snow optical (e.g. Warren 1982), physical (e.g. Lehning et al. 2002) and mechanical properties (e.g. Johnson and Hopkins 2005).

Despite different grain definitions, proper to each application, the general concept of a snow grain can be wrapped up as an *elementary* particle in regard to the *considered property*. *Elementary* implies that the definition of a grain is scale dependent. For instance, the scale can be on the order of a new snow dendrite or of the snowpack depth. Grains are not absolute entities but depend on the subsequent use of the grain representation. *Considered property* means that the grain definition depends on the processes relevant to the considered property. For example, to investigate plastic deformation or impurities in snow, the crystal orientation is crucial and defines the grains. For optical properties, the snow surface area is determinant

and can be used to define a grain size. For mechanical properties, the zones of mechanical weakness or of deformation concentration are crucial and separate the mechanical grains.

In this work, we are interested in the mechanical properties of snow under rapid load (no plasticity). We consider mechanical grains at the scale of around 0.1 mm, i.e, the scale of particles easily detached from the snow mantle. The grain representation of the microstructure reveals the information that is the most informative and crucial for mechanical properties: the bonding system which describes how the grains are stuck to each other.

First the algorithm used to detect the mechanical grains is presented. In particular, the scale of segmentation is expressed as a local contiguity criterion. Then, scalar variables describing the grain representation and its corresponding bonding system are presented. Last, this analysis is conducted on a set of images of snow evolving with isothermal metamorphism.

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2 METHODS: CHARACTERIZATION OF THE SNOW BONDING SYSTEM

2.1 Grain segmentation algorithm

The zones of mechanical weakness are detected with a local geometrical criterion combining curvature and constriction area. The algorithm is illustrated on a simple 2D binary slice of snow (Figure 1a) and consists in the following steps:

- Computation of the principal minimal curvature C_{min} on the entire volume (Figure 1b). Potential necks can be distinguished from grains because they present concavities, i.e. negative C_{min} (red on Figure 1b).
- Detection of potential necks with a watershed pre-segmentation on the C_{min} map (Figure 1c),
- Optimisation of the pre-segmentation (Figure 1d.) by minimising the overall contact area in the potential necks (gray in Figure 1c) and by merging grains that are too stuck to each other, i.e. that satisfy the criterion $S_{int} < c$ ($S_{int} + S_{ext}$) where S_{ext} is the exterior surface of the grain, S_{int} its contact surface with another grain and c a segmentation parameter called contiguity indicator. Contiguity is defined by the portion of the grain surface being in contact with the neighbouring grains, and takes a value between 0 and 1.

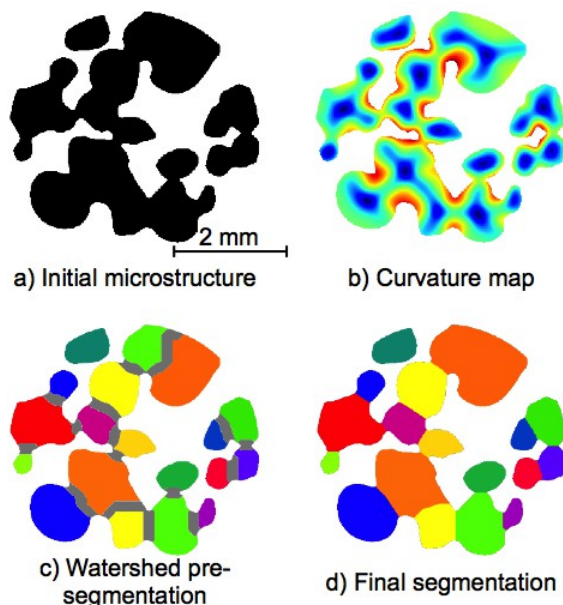


Figure 1: Description of the grain segmentation algorithm.

Details of the image processing can be found in (Hagenmuller et al. 2013). Comparisons with finite-element mechanical simulations have

shown that the considered geometrical criterion is able to detect most of the local mechanical weaknesses.

2.2 Segmentation scale

As shown on Figure 2, the grain segmentation depends on the contiguity indicator c . Quantitatively, on the sample presented in Figure 2, $c=1/3$ (respectively $c=1/7$) yields 272 grains (resp. 178 grains) with a contact area of 9.7% (resp. 4.9%) of the surface area. Actually, the contiguity indicator c defines a segmentation scale i.e. a depth in the hierarchical tree of segmentations. The existence of a segmentation scale is intrinsic to the definition of mechanical grains. For instance in the field, different grains can be obtained depending on the force applied to separate them, which defines the segmentation scale.

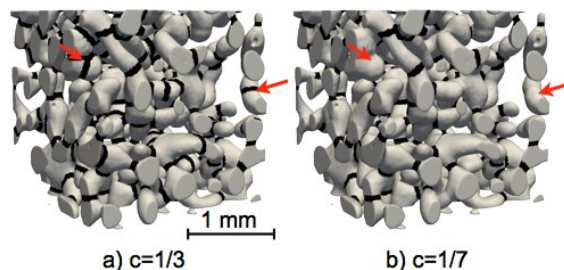


Figure 2: Grain segmentation of a sample of rounded grains obtained with two different values of c . The bonds are shown in black and some differences are emphasised with red arrows.

2.3 Description of the bonding system

Usually the mechanical properties of snow are presented and organised as functions of its density. However, the parametrization of mechanical properties with density shows an important scatter for a given density (Mellor 1975). Therefore, Shapiro pointed out that "it is necessary to characterise the microstructure along with determining the density in order to derive indicators of the mechanical properties of snow" (Shapiro et al. 1997).

The bonding between snow grains has long been believed to be one of these indicators, if not the most important. It is a critical indicator for mechanical properties because it controls almost completely the paths of stress inside the snow microstructure.

a) Direct analysis

Once the microstructure is decomposed into individual particles, with a given segmentation scale, the bonding system can be directly quantified with structural variables. We focus on two main variables: contiguity and specific grain

contact area (SGCA). The overall contiguity measures the degree of freedom of the grains. The SGCA is defined as the ratio of the contact area and the mass of ice. It has long been thought to be a good mechanical indicator (Voitkovsky et al. 1975) because it is a measure of the surface of force exchange. Both variables can be also computed in 3D as vectors, so that they may reveal potential bonding anisotropy.

The direct analysis of the bonding system is completely dependent on the grain segmentation and so, as explained previously, on the contiguity indicator c . The relative evolution of the bonding system variables can be followed during metamorphism and can reveal qualitative features (see section 3). However, the relevant segmentation scale might vary between snow types. Moreover, for a given load, some chains of grains might be activated while the rest of the ice matrix does not support any load. Structural effects at the scale of grain clusters distributes the mechanical importance of bonds. Therefore, absolute values for contiguity or SGCA are difficult to interpret.

b) Minimal cut

We propose an alternative characterisation of the bonding system which is not directly based on the grain segmentation. It results from numerical simulations or experiments of the failure of snow that a sample is generally not entirely damaged during a mechanical test. The failure is localised on a certain surface of the sample that corresponds to few bonds of the whole bonding system. The failure properties of the whole snow sample are expected to depend mostly on the properties of these failed bonds. Especially, there exists a surface of minimal area that separates the sample into two parts (Figure 3). On this surface of minimal cut, the mean stress is greater than on average. Consequently, the area of the min cut surface is expected to be an indicator of the failure properties of snow (Ballard and McGaw 1965). An analogue problem can be found in the study of mechanical properties of trabecular bones whose architecture is similar to the snow microstructure. Tabor (2007) conjectured that "localized failure of trabecular bone is related to presence of a surface of minimal cut (a surface separating the analyzed trabecular sample into two disjoint parts in such a way, that the separation requires removal of minimal possible amount of bone material), properties of which determine the mechanical properties of a whole sample".

The minimal cut area can be computed directly on the 3D image of the microstructure but is then limited to binary image of size less than 400^3 voxels, because of memory usage (6

Gb RAM). The grain representation enables its approximate computation on image of any size because the grain segmentation can be performed locally and the bonding system can be represented by only thousands of nodes and edges. For instance, the sample presented in Figure 3 is composed of 4,630,412 voxels but the bonding system is represented only by 272 grains and 315 bonds. The min cut area computed on the bonding system might be slightly underestimated because some bonds of the min cut surface might be undetected in the grain segmentation. However, for relevant segmentation scales (c in $[1/10, 1/2]$), the underestimation is less than 10% compared to the min cut area computed on the whole 3D image.

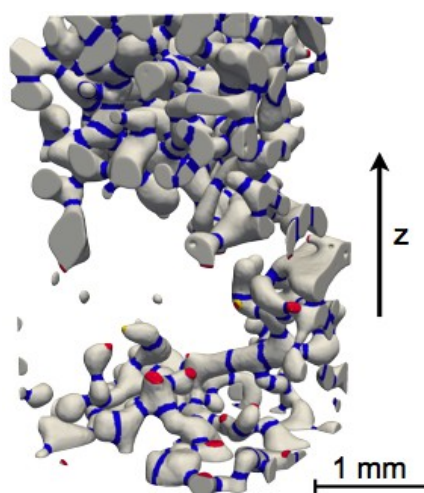


Figure 3: 3D example of minimal cut (red) separating the top and bottom faces of the sample composed of rounded grains. The sample was cut in two parts and the upper part was translated in the vertical direction. Bonds not participating to the minimal cut are plotted in blue. The minimal cut area is here equal to only 7% of the mean horizontal cross-sectional area.

3 RESULTS: EVOLUTION OF THE BONDING SYSTEM WITH ISOTHERMAL METAMORPHISM

3.1 Dataset

The analysis of the bonding system was performed on a series of snow images obtained under a three-month experiment of equilibrium metamorphism at -2°C . This experiment, which is described in detail in the work of Flin et al (2004), consisted in:

(1) taking several snow samples at different stages of metamorphism from an apparently homogeneous layer initially constituted of fresh snow.

(2) acquiring 3D images of these samples by X-ray absorption micro-tomography with a voxel size of $4.91 \mu\text{m}$. Images were then binary segmented with a threshold derived from visual analysis of the grayscale histogram, and downsampled by a factor of two, i.e. to a voxel size of $9.82 \mu\text{m}$.

The following results were obtained on seven 2.5^3 mm^3 samples of this isothermal dataset.

3.2 Evolution of the bonding system

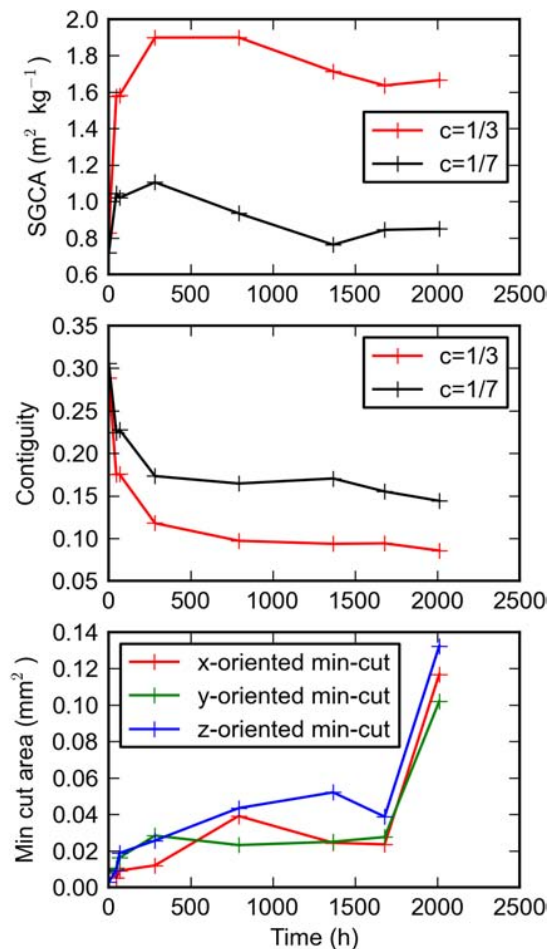


Figure 4: Evolution of bonding structural variables with time and isothermal metamorphism. SGCA and contiguity were computed for two different values of c . The min cut area was computed in three directions. Two grain segmentations scales ($c=1/3$ and $c=1/7$) were tested and did not impact the computed min cut area.

Figure 4 shows the evolution of SGCA, contiguity and min cut area on the set of snow images. SGCA increases strongly during the first 200 h, indicating the creation of new bonds and the strengthening of existing bonds. After 200 h, SGCA tends to decrease more or less depending on the segmentation scale. In this

time range, the contact area still increases but slower than density. The increase of the contact area with time indicates a strengthening of the bonding system because of sintering, and confirms earlier observation on 2D slices of snow (e.g. Baunach et al. 2001) or based on the snow micro-penetrometer signal (Herwijnen and Miller 2013). Contiguity decreases with time, indicating that the “degree of freedom” of the grains is decreasing. Nevertheless, the observed absolute values on SGCA and contiguity depend strongly on the segmentation scale.

On the contrary, the minimal cut area is an intrinsic parameter of the snow microstructure. Its dependence on the segmentation scale is negligible for the tested c values. The minimal cut area also increases with time in all directions. The minimal cut area is slightly larger in the plan oriented by the vertical direction z because of gravity effects that enhance the vertical bonding. The representative volume of the min cut area is expected to be quite large because it is an extreme characteristic (min area of all possible cut surfaces). For instance, the min cut area at 2000 h (Figure 4) is over-estimated because the tested volume (2.5^3 mm^3) presents a few thick chains of grains which might be not representative of the whole microstructure.

4 CONCLUSION

In conclusion, the decomposition of the snow microstructure into individual mechanical grains is of great interest because it simplifies 3D images of snow to its elementary and mechanically crucial description as a bonding system. This grain representation could be used for discrete-element modelling or to efficiently compute complex variables as the minimal cut area.

However, the interpretation of contiguity and SGCA from this representation is challenging because mechanical grains are not absolute entities but are relative to a given segmentation scale. Nevertheless, qualitative trends indicating sintering with isothermal metamorphism are in good agreement with previous observations.

The minimal cut area shows a clear strengthening of the bonding system with isothermal metamorphism and is able to detect the effect of gravity on sintering. It is a promising indicator of potential stress and thermal fluxes. A confrontation with mechanical and thermal measurements would be interesting.

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