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Characterization of the snow microstructural bonding system through the minimum cut density

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ABSTRACT

Snow density is commonly used to phenomenologically parameterize other snow properties such as strength or thermal conductivity. However, density is insufficient to fully characterize the variety of microstructures, as revealed by the existing scatter in the parameterizations. This can be explained by the role of bonds which are almost as important as grains to describe the macroscopic properties of snow. A quantification of the narrow constrictions or bonds between snow grains is thus essential to accurately parameterize snow properties. In order to characterize the reduced thickness of the ice matrix at bonds, we introduce a new microstructural indicator, *the minimum cut density*, ρ_{mc}. This variable quantifies, on three-dimensional (3D) microtomographic images of snow, the minimal effective density of a surface that disconnects two opposite faces of the sample. The obtained minimum cut density values are surprisingly low, in the range [0.2, 35] kg m^{-3} for the tested samples with density in the range [100, 350] kg m^{-3}. This reveals the high variability and weak connectivity of the bonding system in snow. Structural anisotropy of faceted crystals and depth hoar is also well characterized by the minimum cut density. To evaluate the physical and mechanical relevance of this microstructural indicator, we estimate the thermal conductivity and the Young's modulus of the studied snow samples through microstructure-based simulations. An excellent correlation is found between the Young's modulus and the minimum cut density ($R^2 = 0.97$). In particular, the minimum cut density well accounts for the anisotropy of the Young's modulus in faceted snow types. The correlation of thermal conductivity and minimum cut density is also highly significant ($R^2 = 0.88$) but not better than the parameterization with density ($R^2 = 0.92$). We show that this difference is mainly due to the role played by the thermal conduction of air.

1. Introduction

Snow properties, such as strength and thermal conductivity are critical for diverse applications like the forecasting of avalanche hazard (Schweizer et al., 2003) or the computation of the surface energy balance in snow-covered areas (Dadic et al., 2008). The mechanical and physical properties of snow are tied to its microstructure, i.e. the three-dimensional configuration of ice and pores.

The snow density is commonly used as a microstructural indicator to parameterize snow properties. However, it is insufficient to fully characterize the snow microstructure, as shown by the important scatter of physical and mechanical properties corresponding to a given density, revealed for strength and Young's modulus by Mellor (1975), for thermal conductivity by Sturm et al. (1997), for permeability by Arakawa et al. (2009), etc. Therefore, it is necessary to better characterize the microstructure along with determining the density in order to derive indicators of the mechanical and physical properties of snow (Shapiro et al., 1997).

In the last decade, the specific surface area (SSA) has gained significant interest for the modeling of the physical and chemical properties of snow because it is an indicator of potential exchanges with the surrounding environment. For instance, SSA can be used to quantify the adsorption of chemical species (Albert et al., 2002) or light scattering and absorption (Warren, 1982). However, certain properties, such as strength and thermal conductivity, are not controlled by SSA but are mainly sensitive to the narrow constrictions between grains, also called bonds (Colbeck, 1997). In these bonds, stresses and heat fluxes are larger than in the other parts of the snow structure because the

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constrictions between snow grains reduce the potential paths inside the ice matrix. Therefore, the bonding seems to be determinant to formulate an accurate parameterization of snow properties controlled by fluxes internal to the ice matrix (Colbeck, 1997).

In this paper, we want to geometrically characterize the microstructural bonding system of snow in order to provide a parameterization of snow properties that are mainly controlled by fluxes occurring inside the ice matrix. Different attempts of such a characterization can be found in the literature. They can be divided into two main groups:

1. *Characterizations based on a grain definition*. Most of the characterizations of the bonding system rely on the definition of a grain (e.g. Flin et al., 2011; Gubler, 1978; Kry, 1975a; Shertzer and Adams, 2011). Kry (1975a) defined a grain bond geometrically "as the plane surface of minimum area situated in the neck region of two linked grains". In practice the identification of a neck is relative to a certain threshold of constriction. On two-dimensional (2D) images of snow, Kry (1975a) and Shertzer and Adams (2011) considered that a neck exists if the relative decrease of the hydraulic radius is of, at least, 30% in the neck region. On three-dimensional (3D) images of snow, Flin et al. (2011), Theile and Schneebeli (2011), Wang et al. (2012) and Hagenmuller et al. (2014a) used a threshold on curvature at the necks or on the contiguity of the grains. The main difficulty of these grain segmentation methods is to choose the right thresholds. This choice depends on the algorithm used but also on the type of snow and the property of interest. Once the snow microstructure is segmented into grains, the geometry of the grain assembly can be characterized with structural variables such as the mean grain size, the coordination number, the specific grain contact area, etc. However, the values of these variables are generally sensitive to the grain segmentation procedure. For instance, Kry (1975b) tried to link the specific grain contact area to the elastic modulus of a snow sample subjected to uniaxial compression. He pointed out that the grain definition is partly subjective and observed variations up to 40% in the number of bonds depending on whether the "non-obvious" bonds are taken into account or not (Kry, 1975a). Moreover, he concluded that the specific contact area partially explains the stiffness of the ice matrix, because only a small fraction of the grain bonds support the load. More recently, Shertzer and Adams (2011) observed bonds on 2D slices of microtomographic (μCT) images of snow evolving with temperature gradient metamorphism and used the identified bond surfaces to compute the fabric tensor of the bonding system. Through this fabric tensor, these authors proposed an analytical conduction model that accounts for 43% of the observed increase in the heat transfer coefficient (EHC). However, the order of magnitude of the modeled EHC was relative to an arbitrary chosen bond radius that was not derived from the grains obtained by the segmentation procedure. Generally, the interpretation of variables derived from the grain representation is challenging because grains are not absolute entities but are relative to the segmentation thresholds. The concept of grain is defined according to certain geometrical criteria and thus depends on both algorithm and microstructure (Hagenmuller et al., 2013a, 2014a).
2. *Characterizations based on correlation lengths.* The second approach used to characterize the geometry of the microstructure is based on correlation lengths, which quantify the 3D mean size of the material heterogeneity. Srivastava et al. (2010) used the mean interception length (MIL) fabric tensor along with density to explain the anisotropic stiffening of the snow microstructure with temperature gradient metamorphism. More recently, Löwe et al. (2013) applied the rigorous formalism of second order bounds (Torquato and Sen, 1990) to snow and improved the parameterization of thermal conductivity by including a microstructural indicator of anisotropy Q. The computed lower bound for thermal conductivity is far lower than the values of thermal conductivity estimated through 3D microstructure-based simulations, but the computed bound appears to be highly correlated ($R^2 = 0.96$) to the estimated conductivity, especially in the direction of the thermal gradient for faceted snow types (Löwe et al., 2013). However, the parameterization by Q shows greater scatter in the plane orthogonal to the temperature gradient. Löwe et al. (2013) attributed this scatter to the connectivity of the ice matrix which is "apparently more complex" in the plane orthogonal to the temperature gradient than along the direction of the temperature gradient. In general, the characterizations based on correlation lengths are well suited to quantify the microstructural anisotropy of pores and grains (Calonne et al., 2014) but, by definition, are unable to take into account the bonding for low connected snow types, since in this case the bonds represent a very small part of the entire snow image.

According to this brief review and in order to parameterize snow properties that are mainly controlled by fluxes occurring inside the ice matrix, we propose a microstructural indicator which:

1. takes into account the structural anisotropy of the ice matrix (Calonne et al., 2014; Löwe et al., 2013; Shertzer and Adams, 2011; Srivastava et al., 2010),
2. takes into account the fact that only a subset of the constrictions located in the ice matrix are determinant for the macroscopic behavior of the snow sample (Ballard and Feldt, 1965; Kry, 1975b).
3. is independent from a grain segmentation process but retains the concept of a bond as a "flow limiting valve" (Colbeck, 1997).

We developed an algorithm that computes the minimal connection surface between two parts of a snow sample imaged in 3D by μCT. We call this surface, the minimum cut surface. In the following, the two parts correspond to two opposite faces of a cube of snow. Thus, the minimum cut surface is the surface of minimal area among all the surfaces which disconnect two opposite faces of the snow sample (Fig. 1). In other words, cutting the sample on this surface separates its two opposite faces while yielding the smallest amount of broken ice. The minimum cut density ρ_{mc} is defined as the effective density of the minimum cut surface (see Section 3.1 for detailed definition and computation). This concept is directional since a value of ρ_{mc} can be computed in each direction normal to the sample faces (x, y, z) and is thus suited to quantify the anisotropy of the microstructure. Moreover, the minimum cut surface is composed of only a small fraction of the bonds, the ones that are expected to be the most significant for thermal and mechanical properties. Indeed, as shown in Fig. 1, heat fluxes and elastic stresses are expected to be the highest on the minimum cut surface. A small value of ρ_{mc} is thus expected to limit the overall potential thermal conductivity or to enhance the elasticity compliance. Lastly, computing the minimum cut density does not require the definition of a grain, this concept being independent from a grain segmentation procedure. Actually, the concept of minimum cut density was first theoretically introduced by Ballard and McGaw (1965) who defined the "effective porosity on the failure surface". Ballard and McGaw (1965) and Ballard and Feldt (1965) used this concept to reproduce the snow tensile strength assuming that the stress is homogenous and maximal on the minimum cut surface. However, in the 1960s, no technique was available to efficiently measure this property.

In this paper, we compute the minimum cut density on a set of 3D images of snow obtained by microtomography. Then, as a proof of its physical and mechanical relevance, we relate ρ_{mc} to thermal conductivity and elasticity properties derived from numerical simulations (Calonne et al., 2011; Hagenmuller et al., 2014b) based on the same microtomographic images.

2. Snow images

Numerical computations were performed on 12 microtomographic images of snow obtained from previous field sampling and controlled cold-room experiments. Detailed description of each image is provided