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Quantifying damage in polycrystalline ice via X-Ray computed micro-tomography

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ABSTRACT

The use of X-ray computed micro-tomography (micro-CT) is presented here as a useful tool for the analysis and quantification of damage in polycrystalline ice. Although known to be useful for characterizing damage in many other materials, the use of micro-CT has not yet been adapted to the non-trivial case of also characterizing damage in polycrystalline ice. Samples of polycrystalline ice were tested in uniaxial compression at six different strain rates, spanning four orders of magnitude, from 1×10^{-6} s^{-1} to 1×10^{-3} s^{-1}, and two different testing temperatures of -10 °C and -20 °C. The extent of cracking from each test is characterized via micro-CT imaging and is quantified via a newly proposed variant of the crack density tensor, which accounts for any anisotropy in the mean crack orientation and is shown to be equivalent to the materials anisotropy tensor. To account for anisotropy in the distribution of cracks, an eigenanalysis is also performed. The results show that micro-CT can be a useful tool for both visualizing and quantifying damage in polycrystalline ice and that a 3-D analog of the traditional second-rank crack density tensor can be readily calculated via commercially available software.

1. Introduction

Over the last two decades, the use of X-ray computed micro-tomography (micro-CT) has become a widely used laboratory technique for many applications in materials science and engineering [1,2]. Underlying much of this broad appeal is the ability of micro-CT to nondestructively characterize material microstructures at a micron resolution in three dimensions. To date, micro-CT has been successfully employed to characterize an extensive variety of materials and processes, such as bone porosity [3], brine channels and air inclusions in sea ice [4], the fracture and damage of concrete [5], the microstructural evolution of snow under a temperature gradient [6], fatigue crack propagation in cast-iron [7], etc. Although not nearly an exhaustive list, one area of study where the advantages of micro-CT have not yet been fully realized, is the study and 3-D characterization of damage in strained polycrystalline ice. Developing such an understanding is thought to be of critical importance to better predicting the fracture mechanics of both land-based and sea-based ice flows and is thus the primary focus of this work.

Like many other materials, ice can sustain damage in the form of non-propagating cracks that result from localized strains [8]. The presence of these cracks, in turn, can have dramatic affects on the material properties of the ice, even though the larger body remains fully intact. Understanding the role of deformation and damage in polycrystalline ice, including columnar ice, has been the topic of many laboratory, field, and theoretical studies spanning the past five decades [9–16]. This interest is derived from the broad application of such knowledge, including calving rates of glaciers and ice sheets [17,18], predicting sea ice behavior in the Arctic and Antarctic oceans [19–22], structural engineering of off-shore structures in the polar regions [23–25], and interpretation of the surface characteristics of icy terrestrial bodies [26–28].

In order to quantify and validate the predictions of traditional fracture mechanics, as it would apply to ice I_h, there is often an imaging component of the analysis required for either the investigation of field-collected samples or laboratory tested specimens. This imaging component requires that the actual cracks be imaged such that they can be manually counted, measured, and characterized. This is an important component of the analysis, as the size, type, and number of cracks can act as benchmarks detailing the mechanical history of the ice. For example, the observation of

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"comb-cracks" versus "wing-cracks" along a fault may be indicative of the destabilization mechanism of the body [15], whereas evidence of intergranular versus transgranular fracture may be more telling about the response of the ice to either elastic or plastic deformation [29], respectively.

Similar to many polycrystalline metals and alloys, the study of polycrystalline ice via micro-CT has previously been thought of as a poor choice of materials for micro-CT analysis, as no other microstructural information can be elucidated and x-ray attenuation in ice can be quite high [4]. Given sufficient voiding, cracking, or pore space is present within the material, however, the use of polychromatic x-ray sources has been shown to be useful, predominantly only limited by camera resolution. This has been evidenced by other recent micro-CT studies pertaining to sea ice inclusions [4], the bonding of ice spheres [30], and the metamorphism of ice-snow interfaces [31].

2. Background

2.1. Crack density tensor

A very recent and detailed review of the various ways to measure and quantify damage in polycrystalline ice is given in Snyder et al. (2015) [8] and is not repeated here. To summarize, however, most approaches involve first the concession of a 3-D perspective to a 2-D perspective, such that all cracks within a 2-D plane can be differentiated and then manually measured and counted. Making such measurements is quite tedious work, as both the crack length and the normal orientation of the crack from a fixed point of reference is required. With this information, a dimensionless 2-D crack density tensor α_{2-D} can be derived

$$\alpha_{2-D} = \frac{1}{A}\sum_i \left(c^2 \vec{n}\,\vec{n}\right)_i \tag{1}$$

where A is the cross-sectional area of the sample, c is the crack half-length, and $\vec{n}$ is the unit vector normal to the i th crack of length $2c$ [8,32]. The vector product $\vec{n}\,\vec{n}$ denotes the dyadic, which when summed over all cracks and all orientations, gives a measure of the anisotropy of the measured crack orientation in a tensorial format as a second-rank tensor [8]. If extending to the 3-D case, Eq. (1) simply becomes

$$\alpha_{3-D} = \frac{1}{V}\sum_i \left(a^3 \vec{n}\,\vec{n}\right)_i \tag{2}$$

where V is the sample volume and a is the radius of the i th circular-shaped crack [8,33]. In either format, the benefit of the tensorial representation is that it lends a continuum approach to understanding the damage mechanics of the material [34]. In the case of an isotropic or random distribution of crack orientations, Eqs. (1) and (2) simplify to the scalar (first invariant of the tensor), which is the trace of alpha ($tr(\alpha) = \rho_c$).

2.2. Stereological analysis

Of the many variables that can be calculated with the Bruker CT analysis (CTan) software, that accompanied the Bruker Skyscan 1172 micro-CT that was used in this study, the 3-D stereological analysis is focused on here as perhaps the most beneficial in handling anisotropy and crack density distributions. Originally developed for the analysis of pore space in bone, the stereological analysis makes use of a statistical technique in which a mean intercept length is calculated in three dimensions from within a spherical volume encompassing the user-defined volume of interest (VOI) of the sample. Within this encompassing sphere, lines can be drawn in up to 1,024 different orientations with a spacing that is user-defined, but can be as small as one pixel or "voxel" (a 3-D pixel) apart. Once drawn, the orientation of each line is recorded and the length of each line is divided by the number of times it intercepts an object (voxels equal to 1 on a binary scale), this quotient defines the mean intercept length l. Of importance to note, is that whether or not the line drawn traverses a lone 1 pixel or ten 1 pixels, as long as these pixels are connected, this would only count as one intercept. Thus, phenomenologically, the mean intercept length could also be thought of as a metric for the length between cracks and not necessarily the crack length itself.

For the mean intercept length analysis presented in this study, the number of randomly selected orientations was set to 512 with a 90 μm (5 pixel) spacing. For perspective, this allowed for 53,625 lines to be drawn per orientation within a VOI of 4213 mm^3. Once complete, the number and length of all intercepts over all orientations are related back to the principal axes of the encompassing sphere, such that the three principal mean intercept lengths, l_1, l_2, and l_3 and unit vector orientations, $\vec{e}_1$, $\vec{e}_2$, and $\vec{e}_3$ can be determined. These orientations are solved for via the statistical fitting of an ellipsoid encompassing all mean intercept length values, when each mean intercept length is plotted as a radius anchored at the origin. Originally given in Harrigan and Mann (1984) [36], this process creates the surface of an ellipsoid of the general form

$$Ax_1^2 + Bx_2^2 + Cx_3^2 + 2Dx_1x_2 + 2Ex_1x_3 + 2Fx_2x_3 = 1 \tag{3}$$

where A, B, C, D, E, and F are dimensionless coefficients and x_1, x_2, and x_3 are the principal axes of the original Cartesian coordinate system of the user-defined VOI. $\vec{e}_1$, $\vec{e}_2$, and $\vec{e}_3$ can then be solved for via an eigenanalysis, determining the rotation of the orthogonal principal axes of the ellipsoid from the original axes of the VOI, such that $\vec{e}_1$, $\vec{e}_2$, and $\vec{e}_3$ are the eigenvectors representing the orientations of l_1, l_2, and l_3, relative to the original Cartesian coordinate system of the VOI. Additionally, the eigenvalues E_1, E_2, and E_3, are calculated via an eigenanalysis, which can then be used to define the degree of anisotropy DA of the VOI, where $DA = 1 - \left(\frac{E_{min}}{E_{max}}\right)$. It was also cleverly pointed out in Harrigan and Mann (1984) [35] that the coefficients of Eq. (3) can equally be given as a dimensionless tensor, which they present as the materials anisotropy tensor M, where $M = \begin{bmatrix} A & D & E \\ D & B & F \\ E & F & C \end{bmatrix}$. Given that M is indiscriminate towards the material to which it is being applied, it is proposed in this study that it could also be used as an analog to the tensorial component of Eq. (2). Further demonstrating the many advantages of micro-CT and the commercially available software for micro-CT analysis (CTan), it should be noted that all the variables described above (i.e. l_1, l_2, l_3, $\vec{e}_1$, $\vec{e}_2$, $\vec{e}_3$, E_1, E_2, E_3, DA, and M) can be calculated and given as outputs as part of a 3-D stereological analysis.

To more plainly demonstrate and test the applicability of the CTan 3-D stereological analysis for application to problems concerning crack orientation and crack distribution in solids, two binary test-cases were created and are presented here in Fig. 1. The first, a stack of binary images alternating in layers of pixel values set to either 0 or 1, and oriented such that the 1 layers were perpendicular to the x_3 axis is shown in the upper panel of Fig. 1. The second example, shown in the lower panel of Fig. 1, is the same as that shown in the upper panel but rotated 90°, such that the layers with pixel values equal to 1 are parallel to the x_3 axis. These binary