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Review article

Multiscale modeling of ice deformation behavior

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ABSTRACT

Understanding the flow of ice in glaciers and polar ice sheets is of increasing relevance in a time of potentially significant climate change. The flow of ice has hitherto received relatively little attention from the structural geological community. This paper aims to provide an overview of methods and results of ice deformation modeling from the single crystal to the polycrystal scale, and beyond to the scale of polar ice sheets. All through these scales, various models have been developed to understand, describe and predict the processes that operate during deformation of ice, with the aim to correctly represent ice rheology and self-induced anisotropy. Most of the modeling tools presented in this paper originate from the material science community, and are currently used and further developed for other materials and environments. We will show that this community has deeply integrated ice as a very useful "model" material to develop and validate approaches in conditions of a highly anisotropic behavior. This review, by no means exhaustive, aims at providing an overview of methods at different scales and levels of complexity.

1. Introduction

Ice is a common mineral on the Earth's surface, where it occurs as ice Ih. As ice is relatively close to its melting temperature, glaciers and polar ice sheets deform by ductile dislocation creep at strain rates in the order of 10^{-12} to 10^{-6} s^{-1}. Research on the flow of ice is of direct importance to society as it is needed to understand and predict the effects that global warming could have on sea level rise, glacier retreat, etc. There is also an increasing awareness that ice is a valuable analogue for other minerals and crystalline materials, as it is the only common mineral where this creep can be readily observed in nature and in the laboratory. Numerical modeling has become a key method to link the mechanics of ice from the dislocation scale to that of flowing ice masses.

Most of the efforts made to simulate the ductile mechanical behavior of polycrystalline ice are related to the modeling of ice flow and fabric evolution in the conditions of polar ice sheets or glaciers. Ice is increasingly considered as a model material to validate micro-macro mechanical approaches for materials with a high viscoplastic anisotropy. Most of the modeling techniques presented in this paper are currently used or further developed for other materials. For geological applications, one main limitation could be related to the "one phase" approach for most of these techniques, well adapted to ice. The reader will find, at the end of the paper, a table summarizing the main aspects of each techniques, with application ranges and limitations.

1.1. Mechanical properties of ductile ice

Ice Ih has a hexagonal crystal structure with a c/a ratio of 1.628. This c/a ratio is very close to the 1.633 value for a closely packed structure, but ice is not closely packed (see Schulson and Duval

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(2009) for a recent review). The elastic anisotropy of ice single crystals is small. The Young modulus E only varies by about 30%, depending on the direction of the loading axis with respect to the c-axis. The highest value is along the c-axis with $E = 11.8$ GPa at −16 °C (Gammon et al., 1983).

Single crystals deform plastically essentially by glide of dislocations on the basal plane. There are three equivalent $\langle 1\overline{2}10\rangle$ directions for the Burgers vector, but slip on the basal plane is almost isotropic. In conditions where basal slip is favored, the stress-strain rate relationship after a strain of about 5% can be expressed by a power law with a stress exponent $n = 2 \pm 0.3$ (Higashi et al., 1965; Jones and Glen, 1969; Mellor and Testa, 1969). At similar strain rates, the equivalent stress requested for non-basal slip is about 60 times larger than for basal slip (Duval et al., 1983).

For ice polycrystals deformed under the laboratory conditions (strain rate between about 10^{-8} s^{-1} and 10^{-6} s^{-1} and temperature generally higher than −30 °C), strain is essentially due to intracrystalline dislocation glide. The transient creep regime is characterized by a strong directional hardening until the strain-rate minimum is reached for an overall strain of 1% (Duval et al., 1983). This strain-rate decrease can reach three orders of magnitude. It is associated to the development of a strong internal stress field due to plastic incompatibility between grains (Ashby and Duval, 1985; Duval et al., 1983; Castelnau et al., 2008b). A significant part of the transient creep is recoverable, *i.e.*, on unloading a creep specimen, a reverse creep is observed, with reverse strain which can be more than ten times the initial elastic strain (Duval, 1976; Duval et al., 1983). In the secondary creep regime, isotropic polycrystals deform (at similar stress levels) a 100 times slower than a single crystal optimally oriented for basal slip. In this regime, the minimum strain rate and the stress are linked by a power law, referred to as Glen's law in glaciology (Glen, 1955), expressed through a relationship of the form (1) for temperatures lower that −10 °C.

$$\dot{\varepsilon}_{\min} = A\overline{\sigma}^{n}\exp(-E_p/k_B T) \tag{1}$$

with $\overline{\sigma}$ the applied stress, $E_p = 0.72$ eV and the stress exponent $n = 3$ (Barnes et al., 1971;Budd and Jacka, 1989). A is a constant, k_B the Boltzmann constant and T the temperature. Above −10 °C, $\dot{\varepsilon}_{\min}$ rises more rapidly with increasing temperature and cannot be described by this equation (Morgan, 1991). No grain-size effect is expected for power-law secondary creep at laboratory conditions (see (Duval and Le Gac, 1980; Jacka, 1994) for instance). But a grain size effect was, however, measured during transient creep (Duval and Le Gac, 1980).

At strains larger than 1–2% (tertiary creep regime), dynamic recrystallization is predominant, and new grain microstructures and crystal orientations are generated (Jacka and Maccagnan, 1984; Duval et al., 2000).

At stresses lower than 0.1 MPa, relevant to deformation conditions in glaciers, ice sheets or planetary bodies, there is a clear indication of a creep regime with a stress exponent lower than two. This indication results from both the analysis of field data and laboratory tests, although the difficulty of obtaining reliable data at strain rates lower than 10^{-10} s^{-1} is at the origin of contradictory results (Mellor and Testa, 1969; Barnes et al., 1971; Dahl-Jensen and Gundestrup, 1987; Pimienta et al., 1987; Lipenkov et al., 1997; Goldsby and Kohlstedt, 1997). In particular, Goldsby and Kohlstedt (1997) suggest a grain-size dependence of the ice viscosity associated with this low stress regime, based on laboratory experiments performed on very small grain-size samples. This grain-size effect would be associated with a grain boundary-sliding dominated creep. Its extrapolation to polar ice-core deformation conditions remains controversial (Duval and Montagnat, 2002). Diffusional creep, commonly associated with such conditions in many materials yields a viscosity much higher than that deduced from field data (Lliboutry and Duval, 1985). For a review on ice behavior, see (Duval et al., 2010).

Ice as a model material exhibits a challenging viscoplastic anisotropy owing to the presence of only two independent easy slip systems for the dislocations (basal plane). While five independent systems are required to accommodate an arbitrary deformation in a single crystal (Taylor, 1938), Hutchinson (1977) showed that four systems are required for allowing a hexagonal polycrystal such as ice to deform. Being able to represent and to take into account this anisotropy in micro-macro models which aim at linking the single crystal scale to the polycrystal scale, is of primary interest to the material science community. This anisotropy needs to be accounted for at the dislocation scale in order to build physically-based model for the activation of (poorly known) secondary slip systems. The impact of dislocation induced internal stress fields, but also the characterization and development of highly heterogeneous strain and stress fields within polycrystals, and their impact on fabric development turn out to be of strong importance (Castelnau et al., 1996a; de la Chapelle et al., 1998).

During gravity-driven flow of glaciers and ice sheets, the macroscopic behavior of ice becomes progressively anisotropic with the development of fabrics (or textures, c-axis preferred orientations). This anisotropy and its development depends on the flow conditions, but strongly influences the response of ice layers to imposed stress (see Gundestrup and Hansen (1984); Van der Veen and Whillans (1990); Mangeney et al. (1997) for pioneer field work and modeling on the subject). Indeed, a polycrystal of ice with most of its c-axes oriented in the same direction deforms at least ten times faster than an isotropic polycrystal, when sheared parallel to the basal planes.

Fabrics basically develop as the result of lattice rotation by intracrystalline slip (Azuma and Higashi, 1985; Alley, 1988, 1992). Dynamic recrystallization can have a major impact on fabric development, especially at temperatures above −10 °C close to bedrocks or within temperate glaciers (Alley, 1992; Duval and Castelnau, 1995; de la Chapelle et al., 1998; Montagnat et al., 2009), see Section 5. Questions, however, remain to what extent different recrystallization processes operate as a function of depth in polar ice sheets (Kipfstuhl et al., 2006, 2009; Weikusat et al., 2009).

1.2. Main objectives

Accurate modeling of ice flow under natural conditions is relevant for many scientific objectives, such as the response of ice sheet to climate changes (Seddik et al., 2012), the interpretation of climate signals extracted from ice cores (Faria et al., 2010), the energy balance in extraterrestrial satellites (Sotin et al., 2009), and since a few years, the accurate prediction of sea-level rise that is linked to the behavior of fast-moving coastal glaciers (Gillet and Durand, 2010). In this context, challenges are mainly (i) to establish an ice flow law adapted to low stress conditions, changes in temperatures and impurity content, (ii) to consider the macroscopic anisotropy due to fabric development at the given conditions, (iii) to be able to integrate processes such as dynamic recrystallization that can strongly influence fabric development and the flow law.

The aim of this paper is to present a general overview of the main modeling techniques adapted to ice, and the main modeling results obtained from the single crystal scale to the large scale that is relevant to ice sheet flow modeling. Techniques are highly diverse, from dislocation dynamics (micron scale) to Finite Element methods that are adapted to the whole ice sheet (km scale), via mean-field and full-field micro-macro approaches and coupling with a microstructure evolution models (cm to m scale, limited to a