Ice microstructures and microdynamics

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1. Introduction

Ice occurs as polycrystalline aggregates in which the bulk behaviour is the result of the behaviour of the ensemble of individual grains, and is therefore dependent on the microstructure, that is to say the whole arrangement of grains (size, shape, shape- and lattice orientations), their internal substructure (dislocation density and subgrains), impurities and second phases (bubbles in firn, clathrates and dissolved impurities). Knowledge of ice microstructures is central to our understanding of ice microdynamics. It is also important for our understanding of ice in relation to other materials, such as metals and rocks, and of the controls microstructures exert on macro-scale deformation processes in glaciers, polar ice caps, the sea ice cover and icy planets. The microstructure is a constantly changing and evolving, dynamic entity. Two important processes that change the microstructure are grain growth (driven by surface-energy reduction) and (discontinuous) recrystallisation (driven by strain energy); others include the plastic deformation and fracture of asperities of ice. These are the foci of current research. This themed volume covers glacier ice, polar ice, sea ice and planetary ices, with cross-cutting themes of ice microstructures and recrystalliazation, ice core studies, modelling of constitutive laws, planetary ices and scaling. But the underlying relationship examined is that between microstructures, fabrics and asperities, and deformation. Although microstructural dynamics impacts on almost every aspect of ice behaviour, the topics covered in this volume are currently at the forefront of international research efforts.

2. Recrystallization

Recrystallization is of particular interest in materials science since recrystallisation dramatically changes the properties of a material, notably the mechanical properties such as strength, ductility, and anisotropy. Dynamic recrystallization processes in ice are similar to those observed in rocks and metals [1]. In this volume Chauve et al. [2] describe detailed experiments and microstructural studies investigating nucleation processes during dynamic recrystallization of ice using cryogenic electronic backscattered diffraction (EBSD). While Llorens et al. [3] describe the dynamic recrystallisation during deformation of polycrystalline ice through insights derived from numerical simulations. The physical processes involved in recrystallisation are nucleation of recrystallised grains by local dislocation rearrangements and growth of these grains by grain boundary migration with concurrent consumption of the deformation induced defects by the moving grain boundaries. Since nucleation is triggered by the heterogeneity of the deformed structure and therefore at sites which are not typical for the homogeneously deformed material, recrystallisation kinetics and microstructure evolution are extremely difficult to model or predict. This is the reason that recrystallisation is often referred to as the last unsolved problem in physical metallurgy and that further research is still necessary although the basic phenomenon has been treated in scientific literature for more than 120 years. Solving this problem is as relevant for ice as it is for metals. The flow of glaciers and polar ice sheets is controlled by the highly anisotropic rheology of ice that is close to its melting point. During deformation within an ice sheet, recrystallization processes occur that modify the ice texture and microstructure and therefore affect the flow behaviour. Dynamic recrystallisation controls ice microstructures and rheology under different boundary conditions that range from pure shear flattening at the top to simple shear near the base of the sheets. Llorens et al. [3] have investigated these processes through simulations of viscoplastic deformation in combination with dynamic recrystallisation (ELLE) in ice.

Recrystallisation is intentionally utilized in engineering to optimize materials properties of steels and non-ferrous alloys [4]. The interplay of forming strain, temperature, and time generates a wide spectrum of different microstructures that are associated with different mechanical properties. Metals, rocks and ice, all polycrystalline aggregates, show remarkable similarities in their recrystallisation behaviour. In this respect, hot rolling of a steel sheet, the formation of a mountain belt and the flow of a glacier are therefore highly comparable processes, despite the differences in length and time scale, and the material-specific properties of the individual polycrystals. This has an echo in the study described in this volume of recrystallisation and damage of ice caused by friction of runners against ice in winter sports by Seymour-Pierce et al. [5]. Ice-specific complications arise for example in sea ice, where a second, saline, phase may interact with the polycrystal and significantly modify its microstructure, and hence mechanical and physical behaviour. An example is shown in the study by Marchenko and Lishman [6] on the influence of closed brine packets and permeable brine channels on the thermo-elastic properties of saline ice.

3. Ice core studies

Ice sheets allow us to extract hundreds of thousands of years of climate record. However complex deformation processes occur and still hamper accurate dating of events. This uncertainty in the ice record can be drastic, particularly for the deepest and oldest ice. For the reconstruction of our planet's climate history it is imperative that the mechanisms and processes, such as flow and recrystallisation, that modify this record are better understood and constrained. The variation of microstructures along ice cores also provides a unique image of the flow history of ice caps and glaciers. For example, long-favoured models on the stratification of ice caps are currently being challenged and improved, partly owing to new developments in the analysis of ice-core microstructures (e.g., microstructure mapping) and numerical modelling techniques (e.g., micromechanical modelling). Weikusat et al. [7] describe the physical analysis of an Antarctic ice core drilled at Kohnen Station, Dronning Maud Land, Antarctica (EDML) as a move towards an integration of micro- and macrodynamics of polar ice.

4. Constitutive laws for ice

Ice-sheet modelling has nearly always assumed a constitutive response based on an incompressible, non-linearly viscous law with a temperature dependent rate factor, and used a reduced model (shallow ice approximation) for the momentum and energy balances. Furthermore, the viscous response is commonly taken to be a power law, based on Glen’s 1955 data. Although first-order approximations for constitutive laws have significantly advanced our knowledge of the behaviour of ice, more accurate descriptions of the behaviour of ice are needed, for example to develop predictive models for the future of our planet's ice caps, sea level and climate. Again, the presence of impurities or seawater in pore spaces will have a major impact on flow behaviour. In this volume Middleton et al. [8] describe the influence of particulate mixture of fluorite in ice. Ice-rock mixtures are found in a range of natural terrestrial and planetary environments.

While the bulk flow properties of ice are important, so too are the friction properties of ice in Earth dynamics, for instance in glacier and ice stream flow over bedrock and sediments, in the dynamics of the Arctic Ocean, and also of course in winter sports! Three papers in this volume address friction. McCarthy et al. [9] use an empirical approach of rate and state friction, with parameters derived from laboratory ice-rock friction studies to arrive at a constitutive relation applicable to glacier motion over bedrock. Sammonds et al. [10] test a microphysics and micromechanics based constitutive friction law against intermediate scale experiments on saline ice floes conducted in an environmental basin. Seymour-Pierce et al. [5] consider an energy balance approach when modifying Amontons's Law to model the sliding of runners in the skeleton winter sport,

Close collaboration is needed between microstructure researchers, engineers, planetary scientists and geophysicists to improve constitutive laws. Whatever constitutive law is adopted, the numerical problems of solving three- dimensional unsteady flow equations (thermo-mechanically coupled momentum and energy balances on an unknown evolving domain) – real ice sheet modelling – will be the next formidable challenge.

5. Planetary ices

The exploration of the Martian surface by the rover Spirit, the fly past of Jupiter's icy moon Europa by Galileo and Voyager reaching the distant world of Neptune's moon Triton and beyond (e.g., the Cassini-Huygens mission to Titan) have not only thrilled the public but have produced images of such high resolution that scientists are beginning to unravel the tectonics of these planets with ever greater confidence. Throughout the solar system ices exist. However their compositions vary widely. For instance hydrated magnesium sulfate minerals, such as kieserite ($MgSO4·H2O$), hexahydrate ($MgSO4·6H2O$), epsomite ($MgSO4·7H2O$), and meridianiite ($MgSO4·11H2O$) are likely to be important planetary materials, as are clathrate hydrates. On the icy moons, these hydrated phases have been suggested as possible non-water phases at the surface, and may affect the possibility and rate of solid-state convection within the interiors. On Mars, meridianiite may be the most abundant hydrate mineral on the planet, and is important in studies of the present Martian water budget. While the fundamental laws of mechanics will apply whatever the situation, what differs are the driving forces and the response of planetary materials because of the different environmental conditions to which they are subject. Grain-size dependent flow in Ice I has been suggested as playing an important role on earth [11]. However it has now been shown that a high-pressure polymorph of ice, Ice II, an important planetary-forming mineral, also deforms by grain-size sensitive creep at low stresses. While the effect of particulate matter on behaviour at high homologous temperatures has been shown to be important during deformation [12]. The effect of the increase in strength due to increasing rock particle content [8] will impact models of planetary evolution. While the analyses of deformation fabrics of candidate planetary ices at relevant pressure-temperature conditions are going to be key to understanding their rheology.

6. Scaling

The final theme of the volume is the state-of-the-art in the understanding of microdynamics of ice in relation to the controls micro-structures exert on large-scale deformation processes in glaciers, polar ice caps, the sea ice cover and the icy planets. Weiss and Dansereau [13] analyse the linking across scales for sea ice mechanics. As they discuss this question is not new [14], but has re-emerged because of the analysis of in-situ and remote sensing data of the Arctic sea ice cover, and it is importance in understanding the dynamical response of the Arctic to global warming. The analysis of heterogeneous media is generally handled through homogenization procedures. But issues can arise with this approach [13]. Scaling is also addressed by Sammonds et al. [10] and Weikusat et al. [7] and indirectly by many of the contributors to this volume. Understanding the key underlying relations between microstructures and fabrics and deformation is important for improved large-scale models of glaciers, polar ice, the Arctic ice cover and the icy planets.

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