
Homogenisation of Viscoplastic Properties in Porous Polycrystals Using FFT-Based Methods: Application to the Snow-Firn-Ice Transition

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Abstract

Porous polycrystals include manufactured materials such as metal powders, metallic foams, and polycrystalline nuclear fuels, as well as natural materials like snow. These materials are often subjected to slow loading near their melting point, which involves viscoplastic deformation. Knowledge of their viscoplastic behaviour is thus essential for many applications such as metallic manufacturing, hot forming, or for understanding snow settlement under natural conditions. However, their microstructures can vary widely, significantly influencing mechanical responses. Systematic relationships between the microstructure of highly porous polycrystals and their viscoplastic behaviour remain rarely detailed in the literature. In this study, snow is used as a model material, represented as a collection of ice monocrystals sintered together. Ice is characterized by a strong viscoplastic anisotropy, with distinct stress exponents for soft and hard slip systems. This framework allows for investigating how microstructure influences homogenized viscoplastic behaviour.

The study focuses on the transition between two regimes: (i) in highly porous materials when crystal and pore sizes are comparable, the crystals act as isolated monocrystals; and (2) in denser materials, or when a grain is composed of several crystals, the neighbouring grains constrain the crystal behaviour. To explore this transition, numerical full-field simulations were conducted. Three-dimensional synthetic porous structures were simulated using a crystal plasticity model combined with a Fast Fourier Transform-based numerical solver, designed to handle high material property contrasts.

The numerical experiments led to the development of a homogenized model. Through asymptotic analysis, we demonstrated that a homogenized stress exponent can be defined over a wide range of stresses, even when crystal-scale exponents differ. The influence of microstructural patterns, specifically the solid fraction and intercrystalline surface area, on macroscopic viscosity and stress exponent was then investigated. Our results show that crystal-scale deformation mechanisms are strongly affected by confinement from surrounding grains, which constrains dislocation activity. For dense polycrystals, the stress exponent aligns with the hard system's behaviour. In porous polycrystals, the stress exponent varies between soft and hard system values, depending on their relative activities. By applying this new stress exponent parameterization, we reinterpreted experimental data on snow and firn. This work represents an essential step toward a unified model of porous polycrystal viscoplasticity.

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