



Short communication

The influence of anisotropic diffusion on the high-temperature creep of a polycrystalline aggregate

Shun-ichiro Karato

Yale University, Department of Geology and Geophysics, P.O. Box 208109, New Haven, CT 06520-8109, USA

ARTICLE INFO

Article history:

Received 18 June 2010

Received in revised form 6 September 2010

Accepted 7 September 2010

Edited by: K. Hirose.

Keywords:

Diffusion

Creep

D'' layer

Olivine

Post-perovskite

ABSTRACT

The influence of anisotropic diffusion coefficients on diffusion-controlled high-temperature creep is examined. Anisotropic diffusion affects anisotropy of diffusion-controlled deformation of a single crystal. The shape change of a single crystal by diffusional mass flux is controlled directly by the anisotropy in diffusion coefficients. The rate of shape change of a single crystal by diffusion-controlled dislocation glide is controlled by the anisotropy of diffusion coefficients on the plane normal to the dislocation line. Consequently, if a polycrystalline aggregate is deformed uniformly by diffusion creep, then the rate of deformation is controlled by that of diffusion (of the slowest diffusion species) along the slowest direction. In contrast, when a polycrystalline aggregate is deformed by climb-controlled dislocation creep, the rate of deformation is controlled by the diffusion (of the slowest diffusion species) along the direction where the diffusion coefficient has the intermediate value. The results are applied to olivine and post-perovskite. For olivine, the observed large plastic anisotropy and small anisotropy in diffusion suggests that high-temperature power-law creep is controlled not only by diffusion but also by some other factors such as jog density. For post-perovskite, the results of numerical calculations on the mobility of vacancies would suggest that the viscosity of post-perovskite aggregates is higher than or comparable to that of the perovskite aggregates if the defect concentrations were the same among these minerals. However, currently nothing is known about the defect concentrations in post-perovskite and other coexisting phases, and therefore it is impossible to compare the creep strength among coexisting phases from these results.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

Two recent papers motivated me to examine the role of anisotropic diffusion in controlling the creep strength of a polycrystalline aggregate. Firstly, [Ammann et al. \(2010\)](#) showed, based on numerical calculations, that the mobility of vacancies (at Mg and Si sites) in the post-perovskite phase is highly anisotropic (~ 8 orders of magnitude difference in diffusion coefficient), and the fastest diffusion coefficients of these defects in the post-perovskite phase are much faster than those of Si and Mg in perovskite (and comparable to diffusion of Mg and O in MgO) whereas the slowest diffusion coefficient in the post-perovskite phase is much slower than those of Si and Mg in perovskite. Based on the inferred large diffusion anisotropy, [Ammann et al. \(2010\)](#) discussed that the viscosity corresponding to diffusion creep of a polycrystalline aggregate of post-perovskite is higher than that of perovskite (comparable to that in MgO), but the viscosity corresponding to dislocation creep in post-perovskite is much lower than that of perovskite. Their argu-

ment is based on the premise that diffusion of the slowest species along the slowest direction controls the viscosity of a polycrystalline aggregate deformed by diffusion creep, but the diffusion of the slowest diffusing species along the fastest orientation controls the viscosity of a polycrystalline aggregate deformed by dislocation creep. However, there has been no theoretical analysis on these issues, and consequently the validity of their conclusions is unclear.

Secondly, [Kohlstedt \(2006\)](#) re-examined the connection between diffusion and high-temperature dislocation creep in olivine, and concluded that a classic model of diffusion-controlled dislocation creep (e.g., [Weertman, 1955, 1957, 1968, 1999](#)) applies to olivine. The main argument by [Kohlstedt \(2006\)](#) to support this classic model is (i) the similarity in the activation energy between creep of polycrystalline aggregate and the activation energy of Si (and O) diffusion ([Costa and Chakraborty, 2008; Dohmen et al., 2002](#)), (ii) the near agreement of the amount of water effects on diffusion and creep and (iii) the agreement of predicted strain-rates from a simple model with observed ones. Although the near agreement in activation energy between these processes, based on the recent diffusion measurements cited above, is remarkable, it is not entirely clear if this implies a simple link between diffusion and creep in olivine. There are several issues that need to be

E-mail address: shun-ichiro.karato@yale.edu.

examined. First, Bai et al. (1991) showed that creep behavior of olivine single crystal is complex having a range of activation energy depending on the orientation and thermodynamic conditions. Consequently, Bai and Kohlstedt (1992a), for example, proposed the role of jogs to control the creep rate (see also Karato, 1989). Second, the experimental studies on diffusion also showed very weak anisotropy compared to anisotropy in single crystal deformation of olivine. Third, a diffusion-controlled dislocation creep model is difficult to explain the observed fabric transitions in olivine (Karato et al., 2008).

In order to address these issues, it seems important to examine the link between plastic anisotropy and anisotropic diffusion coefficient. In this paper, I will first briefly review the role of anisotropic diffusion in diffusion creep in a polycrystal, and then develop a model of dislocation climb in a material with anisotropic diffusion coefficient to clarify the link between anisotropic diffusion and the creep strength of a polycrystalline aggregate deformed by dislocation creep. I will show that rate-controlling diffusion in diffusion creep is diffusion along the slowest direction, whereas that in dislocation creep in a polycrystalline aggregate is the diffusion coefficient along the direction in which diffusion coefficient has an intermediate value. Some implications for deformation of post-perovskite and olivine will be discussed.

2. Theory

2.1. Diffusion creep

Although theory of diffusion creep was developed long time ago (e.g., Herring, 1950; Lifshitz, 1963; Nabarro, 1948), there has been no theoretical analysis to examine the influence of anisotropic diffusion. In all of these papers, isotropic diffusion coefficient was assumed. Only paper where the influence of anisotropic diffusion in diffusion creep that I am aware is Yang and Li (1995) where some very specific cases were discussed.

Extension of diffusion creep model for anisotropic diffusion is, however, straightforward. We use a concept that for a polycrystalline material to deform by diffusion creep, the continuity in displacement at grain-boundaries needs to be satisfied (Lifshitz, 1963). A simple case where this condition is met is homogeneous deformation, and I assume that this condition is met. The classic model of diffusion creep shows that for a material that deforms by diffusion creep, strain-rate and stress are related by

$$\sigma = \alpha \frac{RT}{\Omega} \frac{L^2}{D} \dot{\epsilon} = \eta \dot{\epsilon} \quad (1)$$

where σ is stress, $\dot{\epsilon}$ is strain-rate, R is the gas constant, Ω is the molar volume, L is grain-size (I consider volume diffusion for simplicity), D is diffusion coefficient and η is viscosity.

In order to extend this model to anisotropic diffusion, let us consider, first, a single crystal subjected to stress along three directions (x_i , $i = 1, 2, 3$). In the following, I will use the coordinate system where the main axes are parallel to the main axes of a crystal where the diffusion coefficient tensor is diagonal. General conclusions will not be affected by this choice of the coordinate system. By extending the treatment such as a model by Lifshitz (1963) to anisotropic diffusion, I obtain,

$$\sigma_{ii} = \alpha \frac{RT}{\Omega} \frac{L^2}{D_{ii}} \dot{\epsilon}_{ii} \quad (i = 1, 2, 3) \quad (2)$$

where σ_{ii} is normal stress acting on the grain-boundary normal to the x_i direction, $\dot{\epsilon}_{ii}$ is the shortening rate along the x_i direction, D_{ii} is diffusion coefficient along the x_i direction when the force is acting along that direction.

If a polycrystal deforms homogeneously, then strain in each grain must be the same. This means that the stress on individual

grains is different depending on the magnitude of diffusion coefficient, D_{ii} . The total stress of the sample is the arithmetic mean of the local stress, hence,

$$\sigma = \left(\alpha \frac{kTL^2}{\Omega} \left\langle \frac{1}{D_{ii}} \right\rangle \right) \dot{\epsilon} = \eta \dot{\epsilon} \quad (3)$$

where $\langle 1/D_{ii} \rangle$ is the average of $1/D_{ii}$.

$$\eta = \alpha \frac{kTL^2}{\Omega} \left\langle \frac{1}{D_{ii}} \right\rangle \quad (4)$$

Hence I conclude that in diffusion creep of a polycrystalline material made of crystals with anisotropic diffusion coefficient, it is the diffusion coefficient along the slowest direction that controls the viscosity (if one component of diffusion coefficient is zero, a polycrystalline material cannot deform by diffusion creep homogeneously).

2.2. Diffusion-controlled dislocation creep

Let us now consider deformation by dislocation creep that is rate-controlled by dislocation climb. Dislocation climb involves atomic diffusion, and I will consider how anisotropy in diffusion affects the anisotropy in deformation by climb-controlled dislocation creep. The shape change due to dislocation glide is determined by the magnitude of slip for a given slip system, and geometry of shape change is controlled solely by the direction of slip and the orientation of the glide plane. Several slip systems exist for a given crystal and a multiple of slip systems are needed to achieve homogeneous deformation of a polycrystal (von Mises, 1928). At high temperatures, the rate at which dislocation glide occurs is controlled by dislocation recovery that is in turn controlled by diffusion. In this paper, I will consider a case where the rate of deformation by dislocation glide is controlled by diffusion. In such a case, the rate of deformation for each slip system is controlled by the diffusion coefficient relevant to that slip system. Because the homogeneous deformation of a polycrystalline aggregate requires the operation of multiple slip systems (von Mises condition), the rate of deformation of a polycrystalline aggregate is in most cases controlled by that of the most difficult slip system (Kocks, 1970).

In the following, I will examine how the anisotropy in diffusion coefficient affects the choice of the most difficult slip system. I will assume that the creep rate is controlled by the diffusion-controlled climb motion of an edge dislocation (Weertman, 1957, 1999). Under this assumption, the strain-rate for a certain slip system is determined by the rate of dislocation climb for a certain type of an edge dislocation, and the strain-rate is related to the velocity of dislocation climb, v_c , as (e.g., Karato, 2008; Poirier, 1985; Weertman, 1999)

$$\dot{\epsilon} = \rho b v_c \frac{L}{d} \quad (5)$$

where $\dot{\epsilon}$ is strain rate, ρ is the density of mobile dislocations, L is the characteristic length of dislocation glide, d is the characteristic length of dislocation climb, and v_c is the velocity of dislocation climb.

The climb velocity of dislocation is controlled by diffusion and the number density of jogs on the dislocation line, viz.,

$$v_c = \frac{2\pi\sigma\Omega}{RT} \frac{D_{c_j}}{\log(L/b)} \simeq \frac{\sigma\Omega}{RT} D_{c_j} \quad (6)$$

where σ is stress, Ω is the molar volume of diffusing species, c_j is jog density (number of jogs per unit length), b is the length of the Burgers vector, L is the mean distance of dislocations, and D is the relevant diffusion coefficient (e.g., Karato, 2008; Poirier, 1985). In case a dislocation line is saturated with jogs, then $c_j = 1/b$ and the anisotropy in climb velocity is solely controlled by the anisotropy

Download English Version:

<https://daneshyari.com/en/article/4742017>

Download Persian Version:

<https://daneshyari.com/article/4742017>

[Daneshyari.com](https://daneshyari.com)