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Deformation of directionally solidified alloys: Evidence for microstructural hardening of Earth's inner core?

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ABSTRACT

The viscosity of Earth's inner core (IC) plays a key role in its dynamics, being important for understanding IC convection, translation, super-rotation, and development of elastic anisotropy. However, estimates for the viscosity of the IC range from 10^{13} Pa·s to 10^{21} Pa·s. One difficulty in estimating the viscosity is that it is not simply a material property, but it depends on the rheology, *i.e.*, the deformation mechanism, which in turns depends on factors such as the temperature, stress, grain size, and microstructure. To examine the effects of microstructure we have carried out constant strain rate torsional deformation experiments on directionally solidified hexagonal close packed (hcp) Zn-rich Sn alloys at high homologous temperature and atmospheric pressure. The directionally solidified hcp Zn-rich Sn alloys have a microstructure that consists of large, columnar, textured crystals composed of dendrites. This microstructure has been proposed for the IC, and hcp Zn at atmospheric pressure serves as an analog for hcp iron under IC conditions, including a likely basal slip (0001) <12’10>, along with some prismatic slip (101’0) <12’10> associated with twinning. The measured torque (or stress, which is a function of the geometry and deformation mechanism, which in turn depends on the grain size) continues to increase past what one would expect for steady state deformation, indicative of hardening. We are yet unclear as to the origin of the hardening, but our hypothesis is that it may involve the relatively few slip systems available in hcp systems, and the large, textured grains of directionally solidified alloys, so that not all strains are easily accommodated by the available slip systems. The semi-brittle behavior of the alloy also supports this hypothesis. An inner core with a textured, columnar microstructure might therefore be harder than estimates of its shear strength might predict.

1. Introduction

In the paper that motivated this commemorative issue of *Comptes rendus Geoscience*, Poupinet et al. (1983) discovered anomalous wave propagation in the inner core, which was soon interpreted in terms of inner core elastic anisotropy (Morelli et al., 1986; Woodhouse et al., 1986), where the direction parallel to the spin axis is 3–4% fast. Since then there has been considerable research on the inner core, investigating its structure seismically (see Souriau, 2007 for a review), and trying to understand the origin of the structure using mineral physics and geodynamics (see Deguen, 2012; Sumita and Bergman, 2014 for reviews).

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Explanations for inner core elastic anisotropy include a shape preferred anisotropy (Singh et al., 2000), or a lattice preferred orientation (also known as texturing). The latter could be caused by solidification (Bergman, 1997, 1998; Karato, 1993) or by deformation. Deformation could be driven by convection (Buffett, 2009; Cottaar and Buffett, 2012; Deguen and Cardin, 2009; Gubbins et al., 2013; Jeanloz and Wenk, 1988), the liquidus not aligned with the gravitational equipotential (Yoshida et al., 1996), Maxwell stresses (Buffett and Wenk, 2001; Karato, 1999), or Ohmic heating (Takehiro, 2011). Neither deformation nor solidification have by themselves, however, been able to explain the varied seismic inferences that include depth (Shearer, 1994; Song and Helmberger, 1995) and longitudinal (Deuss et al., 2010; Tanaka and Hamaguchi, 1997) dependence of the elastic anisotropy, longitudinal variations in the isotropic velocity (Niu and Wen, 2001), and an attenuation anisotropy that itself may vary longitudinally and with depth (Cormier, 2007; Creager, 1992; Souriau and Romanowicz, 1996; Yu and Wen, 2006). Longitudinal variations could be due to long-term mantle control (Aubert et al., 2008) or inner core translation (Alboussière et al., 2010; Al-Khatatbeh et al., 2013; Bergman et al., 2010; Monnereau et al., 2010). Also puzzling is a decrease in the P wave velocity gradient at the base of the outer core (Souriau and Poupinet, 1991), which has been interpreted as a dense fluid layer (Alboussière et al., 2010; Cormier, 2009; Gubbins et al., 2008, 2011).

Making an explanation of these seismic inferences more difficult to pin down is the uncertainty of the elastic

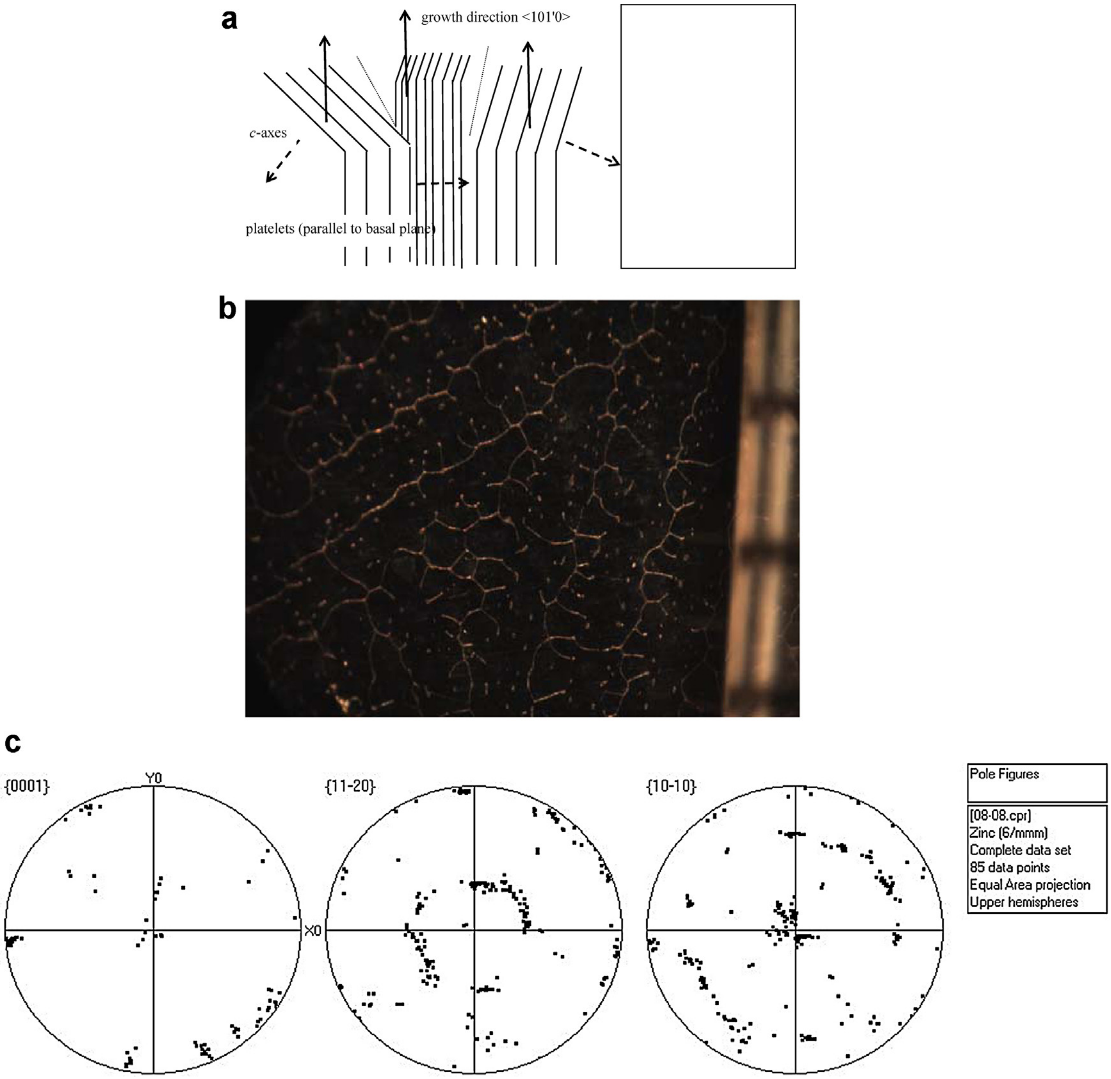

Fig. 1. a. Cartoon showing side view of directionally solidifying hcp alloy. Parallel platelets form a single crystal, with dotted lines showing grain boundaries. Dashed *c*-axes are perpendicular to platelets. b. Micrograph of directionally solidified Zn–3 weight % Sn, transverse to growth. The darker phase is the Zn-rich phase, the lighter, Sn-rich. Platelets, side-branches, and a grain boundary from bottom left to top right are visible. Tick marks represent 1 mm in all micrographs (Color online.). c. A set of pole figures for the sample shown in Fig. 1b, relative to the growth direction. The growth direction is <101'0>, with the *c*-axes primarily transverse to growth. The symmetry of the hcp crystal is such that 101'0 poles near the center also plot on a circle 60° away, and 112'0 poles along a circle at 30° also plot along a circle at 90°.