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Annealing of directionally solidified alloys revisited: No loss of solidification texture in Earth's inner core

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ABSTRACT

Bergman et al. (2010) found experimental evidence for recrystallization and loss of solidification texture during annealing of directionally solidified hexagonal close-packed (hcp) Zn-rich Sn alloys. They suggested that this could support the model of Alboussiere et al. (2010) and Monnereau et al. (2010), in which the Earth's inner core translates convectively eastwards with enhanced solidification in the western hemisphere and melting in the eastern, because as inner core material translates eastwards and anneals it might lose texture, as inferred seismically. The 2010 study hypothesized that the alloys recrystallized rather than coarsened via diffusion due to the very low solubility of Sn in the Zn-rich phase. This study tests this hypothesis by annealing directionally solidified hcp Zn-rich Al alloys, in which there is greater solubility. Indeed, we find the Zn-rich Al alloys coarsen without recrystallization or fundamental change in texture. However, in contrast to the 2010 study the current study also did not find recrystallization in Zn-rich Sn alloys. This might tend to support models such as those by Cormier (2007) and Aubert et al. (2008) where long term mantle control over fluid flow near the base of the outer core might result in a weaker solidification texture in the eastern hemisphere. Although we do believe the results of the previous study are valid because they were repeatable at that time, it shows that there is something subtle that we cannot yet account for, and it remains unclear whether there is loss of solidification texture due to annealing of Earth's inner core.

1. Introduction

Over 25 years ago Morelli et al. (1986) and Woodhouse et al. (1986) inferred that Earth's inner core is seismically anisotropic, with the direction parallel to the rotation axis fast. Seismologists have subsequently found that the direction parallel to the rotation is more attenuating (Souriau and Romanowicz, 1996), that the central inner core may exhibit a different anisotropy axis (Ishii and Dziewonski, 2003; Beghein and Trampert, 2003), and that the anisotropy increases with depth (Song and Helmberger, 1995). They have also found that the inner core is asymmetric, with the western hemisphere exhibiting greater elastic anisotropy (Tanaka and Hamaguchi,1997; Irving and Deuss, 2011), slower direction-averaged *P* wave velocity (Niu and Wen, 2001), and less overall attenuation (Cao and Romanowicz, 2004).

Based on laboratory experiments Bergman et al. (2005) suggested that convection in the outer core might be recorded in the solidification texture of the inner core, and Aubert et al. (2008) explored in more detail the possibility that the hemispherical variations of the inner core might be due to thermal variations in the lower mantle exerting long term control over convection in the outer core. Gubbins et al. (2011) also explored whether these thermal variations could result in hemispherical melting of the inner core and hence provide an explanation for a decrease in the *P* wave gradient at the base of the outer core (Souriau and Poupinet, 1991). In these latter numerical calculations there is melting in the west and enhanced solidification in the east, and Cormier (2007) has suggested ways in which hemispherical variations in heat flow could be compatible with the seismic inferences.

In contrast, another possibility to explain the dense layer at the base of the outer core is that the inner core is translating eastward due to convection, solidifying in the west and melting in the east (Alboussiere et al., 2010). As the recently solidified iron alloy crystals move eastward they anneal and undergo grain growth, sufficient to explain the hemispherical differences in seismic P wave velocity and overall attenuation (by means of scattering; Monnereau et al., 2010). Bergman et al. (2010) found that directionally solidified, hcp Zn-rich Sn alloys that exhibited dendritic microstructure recrystallized as they annealed. Accompanying the

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recrystallization and grain growth was loss of the solidification texture, which could thus be the cause for stronger texture in the west. Although the sharpness of the transition between hemispheres (Waszek and Deuss, 2011) might argue against this explanation, Geballe et al. (2013) suggest a translation model could be compatible with sharp hemispherical boundaries if the single crystal elastic anisotropy is as high as the 12% suggested for the body-centered cubic phase by Belonoshko et al. (2008).

The hypothesis suggested by Bergman et al. (2010) is that the recrystallization is driven by the high surface energy between the two phases, with the recrystallized microstructure showing less boundary area than the original solidification dendritic microstructure. Recrystallization occurred rather than diffusive coarsening via Ostwald ripeneing (Marsh and Glicksman, 1996) because the solubility of Sn in Zn is very low, so that diffusion of Sn through the Zn-rich phase is very slow. Bergman et al. (2010) suggested that the hemispherical variation in inner core elastic anisotropy might result from the loss of texture that accompanies the recrystallization.

To test the hypothesis that recrystallization of the dendritic microstructure results from the low solubility of Sn in the Zn-rich phase, we have carried out similar annealing experiments on hcp Zn-rich Al alloys, which exhibit greater solubility of the alloying element in the Zn-rich phase. Annealing is the process during which a material is brought to a high temperature below the temperature where melting is complete, speeding up the time to reduce high energy microstructural features such as dislocation networks, grain boundaries, and intragranular interphase boundaries. We also carried out similar annealing experiments as two years ago, on hcp Zn-rich Sn alloys.

We use hcp Zn-rich alloys because iron under inner core conditions is likely hcp (Tateno et al., 2010), and because the core is not pure iron-nickel, but is rather some 8% less dense (Birch, 1952). We begin with a dendritic microstructure, which takes the form of platelets in hcp materials (Figs. 1a and 2a), because the inner core is likely growing with such a structure as a result of directional solidification (Fearn et al., 1981). The alloys are comprised of two phases with mass and liquid fractions fixed by the phase diagrams (Fig. 3a and b). The secondary phase in our experiments (Sn or Al-rich) is liquid at the annealing temperature, as is likely in the inner core, though the liquid fraction is low though uncertain (Fearn et al., 1981; Vocadlo, 2007).

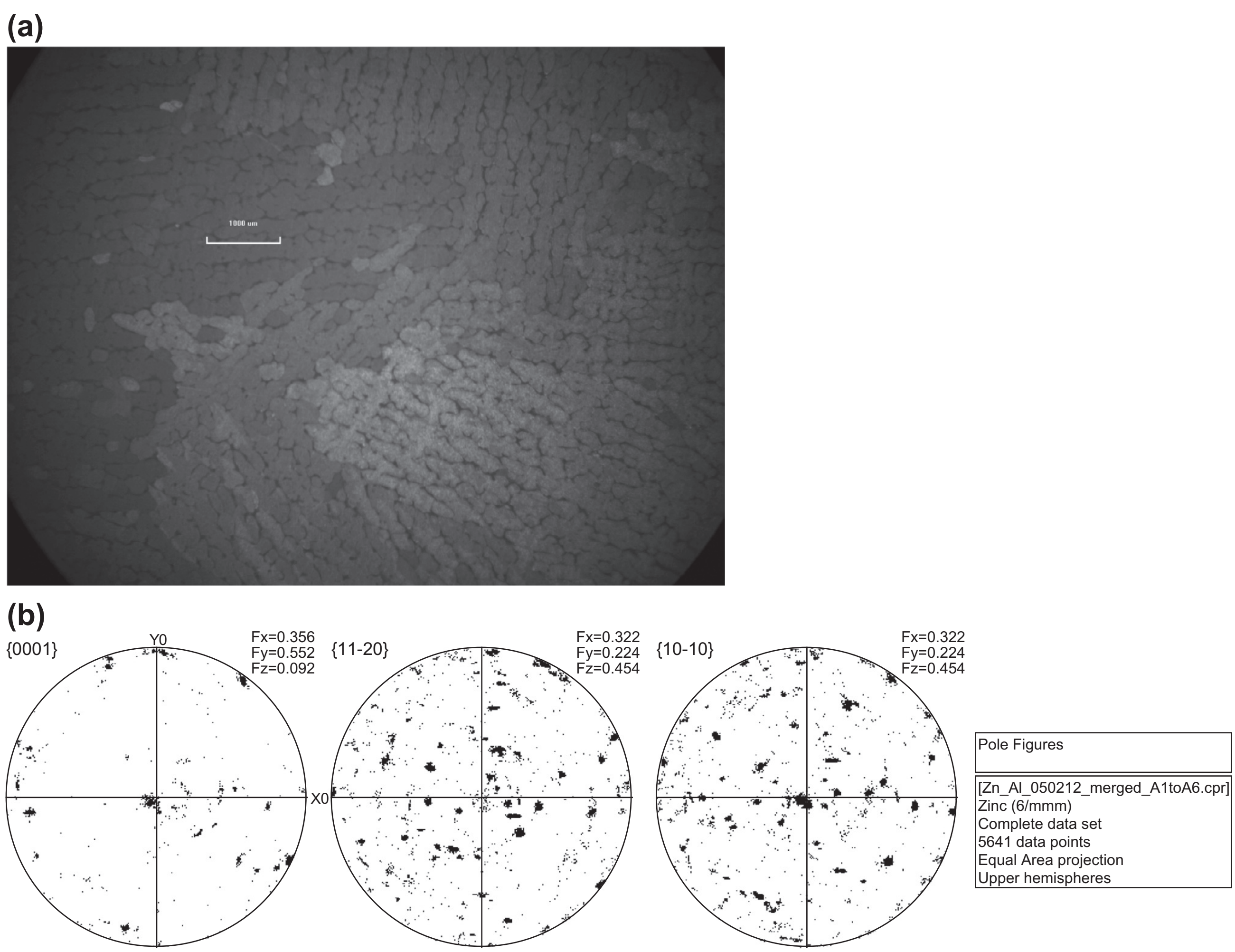

Fig. 1. Directional solidification microstructure and texture. (a) Micrograph of directionally solidified Zn-3 wt-pct Al, transverse to the growth direction. The primary Zn-rich phase is light, the Al-rich phase is dark. Parallel platelets are part of a single crystal, and a grain boundary lies between two sets of parallel platelets. For all micrographs (except 5a) the bar length is 1000 μm. (b) A set of pole figures for the sample shown in Fig. 1a, relative to the growth direction, showing the growth direction is in the 101′0 direction, 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°. For reasons that are unclear EBSD data for Zn–Al always shows much more scatter than for Zn–Sn.