Stress induced interconnection of core-forming melt in a bridgmanite matrix: Implication for percolation in deep mantles of large planets
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Introduction: Planetary cores form from the segregation of iron alloy from silicate mantle. When the mantle reaches the sub-solidus temperature after cooling of a magma ocean, the efficiency of the segregation of metallic melts from a solid silicate matrix is controlled by the dihedral angle between the two melt-solid interfaces. Metallic melt percolation in the solid mantle is commonly excluded at pressures between 25-50 GPa because the dihedral angle between the interfaces of the silicate mineral and metal sulfide melt is higher than the critical value of 60°, demonstrated by experiments carried out under hydrostatic conditions [1-3]. The high dihedral angle would prevent the formation of an interconnected melt network in the silicate mantle. However, the solid silicate mantle may not be static but continuously flowing due to the isostatic adjustment of silicate mantle after a large impact and the heat induced mantle convection [4]. Such flows may enhance interconnectivity. The metallic melt could efficiently descend through such interconnected networks.

In this study, we compared the percolative behavior of liquid iron alloy in a bridgmanite matrix under deformed and undeformed conditions. Our experiments demonstrate that percolation under deformed conditions could be a core-forming mechanism in the deep mantles of planets.

Method: A sintered aggregate of 95% volume of bridgmanite and 5% volume of Fe-S alloy with 6 wt.% sulfur was first synthesized using a multi anvil apparatus at 25 GPa and 1873 K. The synthesized sample was recovered and shaped into a 600-μm disk with 200 μm thickness and put into a Pt tube. The sample surround by the Pt tube was sandwiched between two 45°-cut crushable alumina pistons in a MgO cylinder. Two additional alumina pistons were placed at the end of the MgO sleeve and then placed in a 8 mm octahedral assembly with Re heater.

The cell assembly was first pressurized to 25 GPa and heated to 2100 K and then kept for 20 minutes to relax the deviatoric stress in the specimens. For the deformation experiments, the oil pressure was further increased at a rate of 41 tons/hr. The different compressibility of alumina and MgO capsule results in a deviatoric stress on the sample that leads to a shear of the sample. After deformation for about 2 hours, temperature was quenched and pressure was slowly decreased to ambient condition. The total strain (γ) is estimated from the relative displacement of the two 45°-cut pistons. In parallel, we conducted experiments without deformation for 2 hours to check the melt textures in the undeformed sample. The experimental products were polished and the melts textures were observed by the scanning electron microscope (SEM).

Results: The metal melts in the undeformed sample exhibits isolated pockets, whose average apparent dihedral angle is 77°. The distribution and topology of the metal melt (Fig. 1a, 2a) are similar to those reported in previous studies [2, 3]. In contrast, the deformed sample (γ ~ 0.1) shows alignment of melt pockets. This melt-preferred orientation forms an angle of 15° from the shear plane and consists of elongated melts pockets and isolated pockets (Fig. 1b, 2b).

![Figure 1. SEI of melt structures in the undeformed (a) and deformed (b) sample. Scale bar is 10 μm.](image-url)

The interesting observation is that Pt element is found throughout the melts in the deformed sample while only exists locally in the melts near the Pt tube in the undeformed sample (Fig 2). Besides the majority of the Pt-containing melts, ~0.4% volume of Pt-free melts also exists in the deformed samples. The comparison of melts texture and Pt distribution in the melts between deformed and undeformed sample
indicates that an interconnected melt network is formed in the deformed sample.

Figure 2. SEI of undeformed (a) and deformed samples (b) and corresponding Pt mappings (c) and (d). Scare bar is 50 μm

Discussions: Previous studies suggested that deformation can enhance the percolation of liquid Fe alloy, but only focused on percolative behavior at relatively low pressure in an olivine matrix [5-7]. However, the depth of magma ocean in the Earth may already reach the pressure of bridgmanite stability field [8] and bridgmanite lower mantle may also exist in Martian interior [9]. The results from these studies cannot be applied to the liquid metal and solid silicate segregation scenario in the core formation of large planets. Previous studies also suggested that Fe alloy cannot percolate through a bridgmanite matrix under hydrostatic condition [1, 2]. Although one study suggested a small dihedral angle of liquid Fe alloy in a bridgmanite matrix at higher pressure (> 50 GPa) [3], their results may be affected by the mechanical and thermal stress in the diamond anvil cell. Therefore, the mechanism of the final stage of core formation is still unclear. Our results demonstrate that an interconnected network of Fe alloy can form in a bridgmanite matrix under deformed condition. The Fe melts at the base of magma ocean could migrated through this network towards the proto-core. This scenario is also applicable to Mars core formation because bridgmanite layer is expected above the Mars core [9].

The observation of the 0.4% volume of the Pt-free melts in the deformed sample also has important
grounding. The isolated 0.4% volume of melts in the deformed sample may represent the volume fraction of the stranded melts in the Earth mantle after core formation. This melt fraction is consistent with that required to explain the seismic observations on the large low-shear-velocity provinces [10].