Interfacial tension of Fe-alloy liquids under pressure: Size of core-forming liquid in terrestrial magma ocean

In a terrestrial magma ocean, which is considered to form during planetary accretion, liquid Fe-alloy droplets settle through silicate melt and metal segregation occurs in the planet interior (Fig. 1). The size of Fe-alloy droplets in a magma ocean is closely related to both the sinking velocity, i.e., the time scale of metal/silicate separation and the extent of chemical equilibration between Fe-alloy and silicate melt [1]. Therefore, the interfacial tension of liquid Fe-alloy under high pressure is a crucial factor for understanding metal/silicate separation in terrestrial magma oceans.

We have measured the interfacial tension of Fe-Si liquid under high pressure and temperature, combined with synchrotron X-ray radiography to determine the droplet size of core-forming metallic liquid in a magma ocean. High-pressure experiments were performed using a 1500 ton Kawai-type multi-anvil device installed at beamline **BL04B1**. A 2-mm-diameter pellet of Fe-Si powder packed within $Na_2Si_2O_5$ glass powder was placed in a boron nitride capsule. The X-ray beam transmitted from the sample was acquired as an X-ray radiographic image using a high-resolution CCD camera. All experiments were performed at a pressure of 1.5 ± 0.3 GPa and up to 2173 K.

To determine the interfacial tension of the liquid, the sessile drop method was applied. When liquid Fe-alloy rests on the smooth flat solid surface of a capsule in contact with overlying silicate liquid, the liquid Fe-alloy adopts the form of a rounded drop as a result of force equilibrium between gravity and interfacial tension. From the X-ray radiographic images, we obtain the shapes of the liquid Fe-Si droplets at high pressure and temperature (Fig. 2). As the shape of the liquid droplet can be expressed by combining the classical Laplace and Young's equations, we can calculate the interfacial tension of Fe-Si liquid. Further details of this method are described elsewhere [2,3].

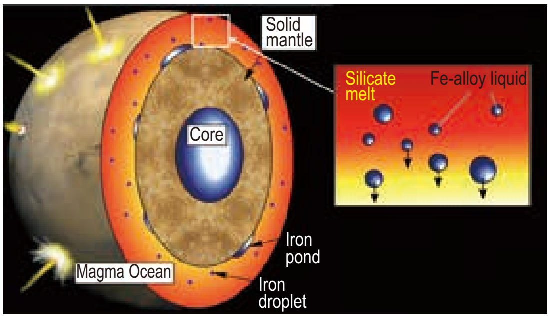

Fig. 1. Schematic view of interior of early Earth. Liquid Fe-alloy droplets settle in the magma ocean during the core formation stage.

The effects of temperature on the interfacial tension of Fe-Si liquid are plotted in Fig. 3(a). The interfacial tension of Fe-Si liquid decreases with increasing temperature [4]. This observed trend might be due to the following reason. Interfacial energy, which causes interfacial tension, depends on the excess energy at the interface compared with the energy of the droplet interior. When the thermal motion of Fe and Si atoms in the Fe-Si liquid increases at higher temperatures, the difference in energy between the interface and the interior may be reduced, thus causing a reduction in the interfacial tension at high temperature.

The interfacial tension decreases with increasing Si content, suggesting that Si behaves as a surface active element that reduces the interfacial tension [4]. The interfacial tension of Fe-Si liquid at 1.5 GPa is plotted as a function of the light element content in Fig. 3(b), together with the data of Fe-S and Fe-P liquids [3]. Comparing the effects of different alloying elements (S, Si, and P) on interfacial tension, S is found to be the most effective in causing a reduction, and silicon has a relatively moderate effect. In contrast, the effect of P is negligible. Therefore, the effects of each light element on the interfacial tension of liquid iron are all different. These trends at 1.5 GPa are similar to those measured at ambient pressure, which suggests that interfacial properties of liquid Fe-alloy are approximately constant, at least up to 1.5 GPa. However, the difference in the interfacial tension among different light elements becomes smaller at higher pressure.

The characteristic size of Fe-alloy droplets in a magma ocean is determined by the force balance

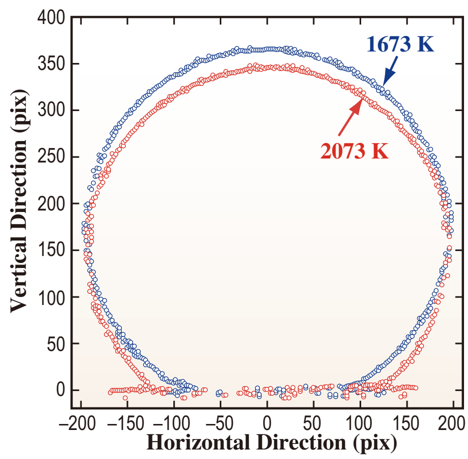

Fig. 2. Interface plots of Fe-Si (Si=25 at%) liquid obtained from radiography images at 1673 and 2073 K.

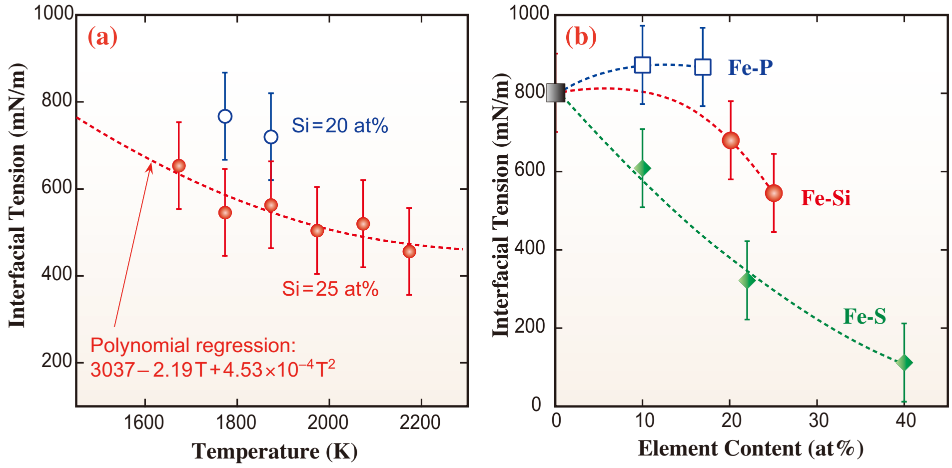

Fig. 3. **(a)** Effect of temperature on interfacial tension. Red and blue symbols represent the interfacial tension of $Fe_{75}Si_{25}$ and $Fe_{80}Si_{20}$ liquids, respectively. Polynomial regression curve is also shown. **(b)** Interfacial tension as a function of light element content at 1.5 GPa. Red circles show results for Fe-Si liquid at 1873 K. Black square, green diamonds, and blue squares show the results for Fe, Fe-S, and Fe-P liquids at 1.5 GPa and 1943 K, respectively [3].

between the viscous stress, which causes disruption of the droplet, and the interfacial tension, which inhibits breakup and disruption [1,5]. On the basis of the results of the current and previous studies on the interfacial tension of Fe-alloy liquids, the settling velocity for Fe-alloy liquids in a magma ocean is calculated at 1.5 GPa and 2500 K, assuming that the interfacial tension of Fe-alloy liquid in the magma ocean is the same as that in $Na_2Si_2O_5$ liquid. The calculated setting velocity of liquid Fe-alloy is plotted as a function of silicate melt viscosity in Fig. 4. The droplet size of Fe liquid is calculated to be 7 – 11 mm if the viscosity of the magma ocean lies in the range of 10^{-2} – 10^{-1} Pa-s. The droplet size of Fe-Si liquid is found to be larger by ~15% than that of Fe liquid. This suggests that the effect of Si on the density is stronger than its effect on interfacial tension, which therefore leads to the increase in droplet size. S causes a significant decrease in droplet size (*ca.* 33% decrease in size) with increasing S content from 10 to 40 at%. The settling velocity of droplets in the magma ocean decreases with increasing Si and S contents. In particular, the settling velocity of $Fe_{60}S_{40}$ liquid decreases significantly (~46%) compared with that of Fe liquid.

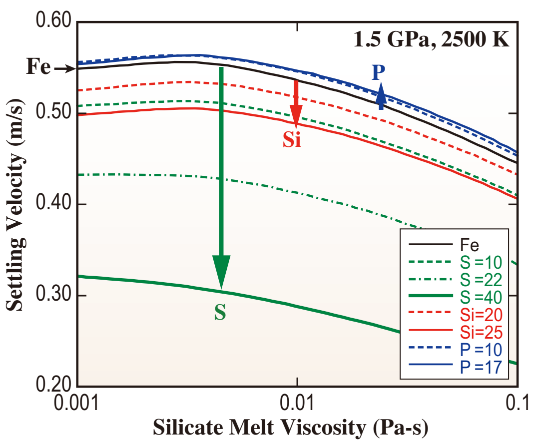

Fig. 4. Calculated settling velocity of Fe-alloy liquids as a function of silicate melt viscosity. Green, red, and blue arrows indicate the alloying effects of S, Si, and P on the settling velocity of liquid Fe.

If the core-forming liquid is enriched in S, the droplet size and the settling velocity are smaller than those for pure Fe liquid. Hence, chemical equilibrium between the droplet and surrounding silicate melt is established faster. Since smaller droplets tend to be entrained upward by the convective flow of silicate melt [5], smaller Fe-S droplets stay suspended for longer in the magma ocean compared with larger Fe, Fe-Si, or Fe-P droplets. In the present estimates, however, the droplet size and the settling velocity were calculated under the conditions of a shallow magma ocean. Further measurements of interfacial tension at higher pressures are required to determine droplet sizes in a deep magma ocean.

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