Experimental study of iron metal condensation. K. Tatsumi, H. Nagahara, K. Ozawa, and S. Tachibana, 1Dept. Earth Planet. Sci., Univ. Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan, chichaneko@eps.s.u-tokyo.ac.jp

Introduction: Metallic Fe-Ni is one of the most important constituents of chondrites. Isolated large (>100 μm) Fe-Ni metal grains included in CH carbonaceous chondrites are thought to have condensed in the solar nebula on the basis of their chemical compositions that are expected to condense in equilibrium with the solar nebula gas [1]. Some of metal grains in CM [2], CI, and CR chondrites [4] also show Ni-Co positive correlation, and can be condensates from the solar nebula gas [2].

Nickel-iron metal grains in CH chondrites, keeping the compositional zoning during condensation, are expected not to have experienced any thermal alteration [5]. It is also inferred that such metal grains condensed under non-equilibrium kinetic conditions that prevented the zoning profiles from being homogenized. The conditions for condensation of zoned metal grains in the early solar system were discussed based on the growth rate of metallic iron assuming that a condensation coefficient of metallic iron is unity (i.e., all incident iron atoms are incorporated into solid metal without any kinetic hindrances) [5]. However, the condensation coefficient is not necessarily unity and may have dependence on temperature or a degree of supersaturation of iron gas as the evaporation coefficient of Fe metal has dependence on temperature and undersaturation of iron gas [6]. In this study, we have carried out condensation experiments of metallic iron to obtain the condensation coefficient as a function of temperature and supersaturation of iron gas, which will be applied to detailed discussion of condensation of metallic iron in protoplanetary disks.

Method: Gaseous iron, produced by heating a metallic iron plate (12 mm × 12 mm) at 1170°C, was condensed on a molybdenum substrate set in a cooler region of a vacuum chamber. The temperature of the substrate varies depending on the distance from the source: 1020, 750, and 415°C for distances of 54, 73, and 88 mm from the source, respectively. Note that, because the incoming flux to the substrate also depends on the distance from the source, we cannot control the substrate temperature and the incoming flux independently at present. The experimental durations were 6-144, 3-48, and 1-48 hours for condensation temperatures of 415, 750, and 1020°C, respectively.

The weight changes of the source and the substrate were converted to evaporation and condensation rates by dividing by the experimental duration and either the surface area of the source or condensable area of the substrate, respectively. Condensates were observed with a field-emission scanning electron microscope (FE-SEM), analyzed with energy-dispersive spectroscopy (EDS) for chemical composition, and with electron-backscattered diffraction (EBSD) for crystallinity and phase identification.

Results: Condensates were identified to be crystalline metallic iron under all the experimental conditions. The structure of the condensed layer varies with temperatures of the substrate. A porous layer of granular condensates were formed on the substrate at 415°C, while condensates formed a compact layer at 750°C and 1020°C (Fig. 1). The compact layers at 750°C and 1020°C due to annealing. The surface of the compact condensate layer was granular at 750°C and smooth at 1020°C. The crystal size seen on the top of the condensate layer increased with experimental time at 415°C (Fig. 2). On the other hand, the size change of condensates could not be determined at 1020°C because they formed a compact polycrystalline layer.

The weight of the condensates and the thickness of the condensed layer increased linearly with heating duration, but the basic characteristics of condensates, described above, for each condensation temperature seemed not to change significantly with heating duration.

The iron plate source lost its weight linearly with time, and its evaporation rate was consistent with previous evaporation experiments [6].

Discussion: The condensation coefficient of metallic iron was estimated based on weight gain of the substrate and weight loss of the source with taking geometrical effects of the furnace on incoming flux into account. The condensation coefficients, evaluated as a function of temperature, are shown in Fig. 3. The condensation coefficients have little or no dependence on temperature, which is different from the evaporation coefficient with clear temperature dependence [6]. It should be noted that we cannot control the degree of supersaturation in the present experimental setting and the dependence on supersaturation should be examined in future studies.

The condensation coefficient of ~0.7 irrespective of condensation temperatures does not significantly change the discussion for the origin of zoned metal [5], but makes the growth timescale ~40% longer. Kozasa and Hasegawa [7] has modeled the condensation of...
metallic iron in the solar nebula and discussed the growth rates and the kinetic condensation temperature, at which gas species begin to condense, for major refractory condensates (Al₂O₃, CaTiO₃, Mg₂SiO₄, and metallic Fe) in the cooling solar nebula. Although condensation coefficients for all gas species were treated as unity, if the value of ~0.7 is applied to metallic iron, the condensation behavior of metallic iron will be changed. For example, the number density of metallic iron nuclei at the condensation temperature of metallic iron becomes ~0.7 times smaller than the case with the condensation coefficient of unity, resulting in that the mean radius of iron grains becomes 10% larger. Moreover, possible annealing effects seen in experiments at 750°C may suggest rapid coagulation of metal dust particles after nucleation.

In summary, laboratory experimental determination of condensation coefficients of dust species will enable us to make accurate calculations for condensation processes, which include the order of condensation sequence, cooling timescale, and growth rates. Although further experiments are needed, the present study gives an important constraint on the evolution of metallic particle and related silicates.

![Fig. 2. Change of average crystal size with time, which condensed at 415°C. Vertical bars represent mean standard deviations.](image)

![Fig. 1. FE-SEM images of surfaces (left) and cross sections (right) of Fe-metal condensates. Upper panels: 415°C for 96 hours; middle panels: 750°C for 24 hours; bottom panels: 1020°C for 24 hours. White bars with numbers are scale bars (in microns).](image)

![Fig. 3. Condensation coefficients of iron metal as a function of temperature.](image)

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