

# The reproduction experiment of radial pyroxene chondrules using aerodynamic levitator furnace in a reduced condition

Tomoyo Morita<sup>1</sup>, Tomoki Nakamura<sup>1</sup> and Kana Watanabe<sup>1</sup>

<sup>1</sup>Tohoku University, Japan

We performed reproduction experiments of radial pyroxene chondrules (RP chondrules) using the aerodynamic levitator furnace in a reduced condition that simulates the environment in the protoplanetary disk [1]. Chondrules were formed by flash heating of solid precursors and crystallization during subsequent cooling. They show characteristic texture that refracts thermal histories and the local environment of the protoplanetary disk [2]. In this study, we attempt to constrain the thermal history of the RP chondrules, which formed at high temperature by total melting of the precursor material.

The experiments were performed using the aerodynamic levitator furnace at Tohoku University [3]. The sample spheres were levitated by Ar-H<sub>2</sub> gas (Ar = 97 %, H<sub>2</sub> = 3 %), heated to melt by a CO<sub>2</sub> laser (LC-100NV from DEOS), and cooled to crystallize in a non-contact state. The cooling rates were from 1 to ~1000 °C/s in the temperature range from 1600 °C to 500 °C. During cooling small glass particles called "seed" impacted the molten sample to crystallize pyroxene. The furnace was enclosed in an acrylic container and the inside of the container was replaced with Ar-H<sub>2</sub> gas to achieve a reducing atmosphere of  $\Delta IW$  from -1.5 to -0.5. The starting material was a mixture of oxide powders (SiO<sub>2</sub>, MgO, FeO, CaO, Al<sub>2</sub>O<sub>3</sub>, and Na<sub>2</sub>O) with three different compositions similar to natural RP chondrules [4-6]. No metallic Fe was used. During the experiment, images of the samples were taken with a CCD camera (ELMO) and a high-speed monochrome camera (Photron FASTCAM-Net Max). The temperature of the samples was measured with a radiation thermometer (LumaSense Technologies ImpacIN140/5-H). After the heating experiments, the samples were then buried in an epoxy resin and polished. The microstructure was observed and chemical composition was determined using SEM/EDS (Hitachi S-3400N) and FE-SEM/EDS (JOEL JSM-7001F).

The experiment reproduced RP chondrules: radial pyroxene crystals growing from one or more points, mesostasis glass filling in between the pyroxene crystals, and two types of metallic iron with different morphological characteristics. Pyroxene crystals have dendritic shapes with linear surface contours, or are an aggregate of fine crystals similar to that in cryptocrystalline chondrules, indicating rapid crystallization from a supercooled melt. The Mg# of the pyroxene crystals reflect Mg/(Mg+Fe) ratios of the starting materials. Some samples have Fe-rich overgrowth on large (> 1  $\mu\text{m}$ ) Mg-rich pyroxene crystals, suggesting that the rapid crystal growth was followed by continued slow crystal growth due to slow cooling (1-10 °C/s).

The metallic iron in the samples was classified into two types based on the texture: one was primary metal which is variable in size from  $\mu\text{m}$  to mm, crossing the radial pyroxene crystals. SEM observations showed that relatively small (< 10  $\mu\text{m}$ ) primary metals are incorporated into the pyroxene crystals and that radial crystals of pyroxene were aligned along the surface of the larger primary metals. The other was submicron-size metallic inclusions (hereafter secondary metal) that occurred only in mesostasis glass (Fig.1). The secondary metal is spherical or dendritic in shape, sometimes clinging to the surface of pyroxene crystals. In addition, they were found in a portion of the sample, not in the entire sample. Both primary and secondary metals were produced by reduction of Fe oxides due to low oxygen fugacity around the molten samples (Ar-H<sub>2</sub> ambient gas), because no metallic iron was added to the starting material. However, the timing of formation was different between the two inferred from their texture and observation.

The primary metal was formed during total melting of the starting material. We succeeded *in-situ* imaging of the formation of the primary metal using high-speed camera: the metal sphere forms in the melt when the sample was heated for about 10 or more seconds. In addition, the textural observation indicates that the metal solidified in a silicate melt during cooling, prior to the pyroxene crystallization. On the other hand, the

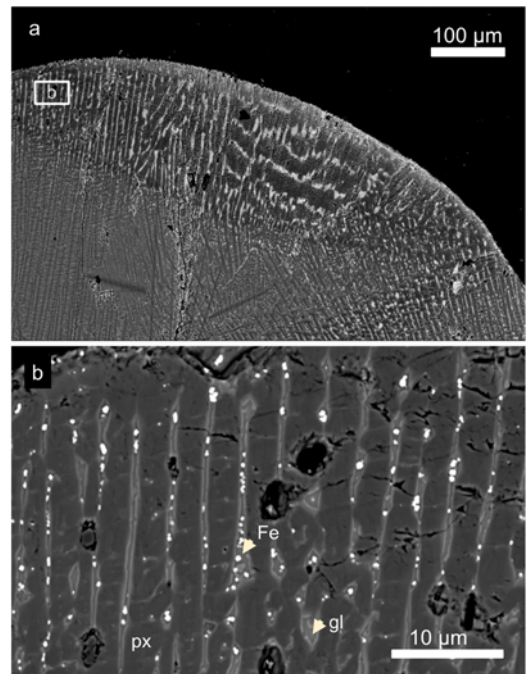


Figure 1. (a) Back-scattered electron (BSE) image of a RP chondrule produced by the experiment. Dendritic radial pyroxene crystals spread over the sample. (b) Enlargement view of the white box in (a). The spherical secondary metals are abundant in mesostasis glasses. Px; pyroxene and gl; glasses.

secondary metal is considered to have formed at temperature between the pyroxene crystallization and the glass transition (mesostasis glass formation). Secondary metal was observed in some samples cooled slowly (cooling rate is 1-10 °C/s) from the crystallization temperature to 500°C, while it was not observed in the glass of samples cooled rapidly after crystallization of pyroxene. The secondary metal formation only by slow cooling is interpreted as the time required for the reduction reaction and for the diffusion of Fe in the glass.

Similar primary type-metal inclusions are found in the natural RP chondrules, suggesting that the large metallic spheres were formed immediately after total melting by the reduction of iron oxide during chondrule formation, or they were present in the precursors. On the other hand, the metallic spheres of submicron size are universally found in natural RP chondrules, and their microstructure is similar to that of secondary metal produced in this experiment. This indicates that RP chondrules cooled at < 10 °C/s after crystallization of pyroxene and before glass solidification in a reduced condition to make secondary metallic inclusions.

#### **References**

- [1] Villeneuve, J. et al. 2015. *Geochim. Cosmochim. Acta* **160**:277. [2] Nagahara. H. 1981. *Nature* **292**:135. [3] Nagashima. K et al. 2006. *Journal of Crystal Growth* **293**:193. [4] Dodd. R.T. 1973. *Earth and Planetary Science Letters* **40**:71. [5] Nagahara. H. 1981. *Memoirs of National Institute of Polar Research* **20**:145. [6] Kita. N.T. et al. 2010. *Geochim. Cosmochim. Acta* **74**:6610.