SEPARATION OF MELTED IRON SPHERES IN CHONDRULES DURING THE CHONDRULE FORMATION. M. Uesugi\textsuperscript{1} and M. Sekiya\textsuperscript{2}, \textsuperscript{1}Japan Synchrotron Radiation Research Institute (JASRI) 1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5198, Japan (uesugi@spring8.or.jp), \textsuperscript{2}Department of Earth and Planetary Sciences, Faculty of Sciences, 33 Kyushu University, Hakozaki, Fukuoka, 812-8581, Japan (sekiya@geo.kyushu-u.ac.jp).

Introduction: Chondrules have a distinctive feature that they are depleted in siderophile elements relative to the solar elemental abundance \cite{1}. Several processes, such as ejection of iron component by high-speed rotation of chondrules during their formation and fractionation in the condensation of chondrule precursor materials from hot nebular gas, are considered to be possible reasons of the iron-chondrule separation \cite{2}. However, this issue is still in the debate. Separation due to physical fission of chondrule and metallic iron part is one of the most probable reasons for the depletion. The fission could occur at the time of chondrule formation, so, if the physical fission is responsible to the depletion of siderophile elements in chondrules, we can obtain important information of chondrule formation processes by investigating the feature. We propose a new viewpoint for the study of this process, based on the theoretical calculation of the separation of melted chondrule and iron sphere at the time of the chondrule formation.

Basics: Consider a melted iron sphere inside of a melted chondrule moving toward the surface of the chondrule. After the iron sphere reaches the surface, strong surface tension of the melted chondrule and iron sphere govern further motion of the iron sphere. So, in order to examine the possibility for the physical fission of melted chondrules and melted iron spheres, the surface energy condition for the process must be estimated.

In the case that a melted iron sphere is outside of a melted chondrule, total surface energy of the system is described as

\[ E_{\text{OUT}} = 4\pi\{T_i r_i^2 + T_c r_c^2\}, \quad (1) \]

where \( T_i \) is surface energy of melted iron sphere, \( r_i \) is the radius of iron sphere, \( T_c \) is surface energy of melted chondrule and \( r_c \) is radius of melted chondrule. On the other hand, if the iron sphere is inside of the melted chondrule, then the total surface energy becomes

\[ E_{\text{LIN}} = 4\pi\{T_b r_i^2 + T_i (r_c^2 + r_i^2)^{2/3}\}, \quad (2) \]

where \( T_b \) is interfacial energy between melted chondrule and iron sphere. The melted iron sphere which exist inside of the melted chondrule automatically ejected to the outside of the melted chondrule at the time that the iron sphere touches the chondrule surface, if total surface energies for those conditions satisfy \( E_{\text{OUT}} < E_{\text{LIN}} \), as long as the viscous energy dissipation is smaller than the difference of these energies. Using Eqs. (1) and (2), this condition can be re-written as

\[ T_i < T_b + (2/3)T_c(r_i/r_c). \quad (3) \]

Surface energies of melted metallic iron and melted silicate are obtained by melting experiments. However, the interfacial energy of melted chondrule and iron is not obtained. In order to obtain the interfacial energy \( T_b \), we formulated and calculated the lowest energy and shape for the state where a melted iron sphere is “on” the surface of a melted chondrule, and compare it with the shape of natural chondrules.

Results and discussion: Figure 1 shows an iron sphere is on the surface of a natural chondrule in Y-81023 (CO3). The radii of iron and chondrule are 200 \( \mu m \) and 50 \( \mu m \), respectively. The chondrule consists of glassy silicate and the iron sphere consists of oxidized iron. In this case, the surface energy of the melted chondrule and the melted iron sphere is around \( T_c = 400 \) erg cm\(^{-2}\) and \( T_i = 1700 \) erg cm\(^{-2}\). Using these physical values of chondrule and iron sphere, we calculated the equilibrium shape. Figure 2 shows some results of the calculations. Interfacial energy used in the calculation is shown under each illustration. The equilibrium shapes that calculated using \( T_b = 1500 \) and 2000 erg cm\(^{-2}\) disagree with the natural chondrules, and the shape calculated using \( T_b = 1800 \) erg cm\(^{-2}\) agrees well with the actual shape of iron sphere and chondrule in natural meteorite. Thus, the value of \( T_b \) for melted iron sphere and melted chondrule is obtained as around 1800 erg cm\(^{-2}\). This
value of $T_b$ always satisfies Eq. (2), irrespective of the radius of iron sphere and chondrule, $r_i$ and $r_c$. This means that once a melted iron sphere that initially inside of a melted chondrule reaches the surface during the chondrule formation process, the iron sphere is immediately ejected to the outside of the melted chondrule. And also, a melted iron sphere which initially outside of a melted chondrule is hard to penetrate into the melted chondrule, because strong surface tension prevents the penetration into the chondrule.

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As discussed above, our calculations show that the iron spheres that consist of metallic iron are easily ejected to the outside of the melted chondrule, if they reach the surface of a melted chondrule during the chondrule formation. If chondrules that melted in the solar nebula have some amount of angular momentum, iron spheres are transported to the surface of melted chondrules and immediately leave from the surface of chondrules. Thus, the ejection of iron sphere due to surface tension would play important role for the origin of the contents of siderophile elements in chondrules.

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