Comparison of Thermal Inertia between Ryugu Sample and Carbonaceous Chondrites

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Introduction: According to the general planetary formation scenario, the Solar System bodies evolved over a long period of time through repeated collision, fragmentation, and aggregation of planetesimals formed in the solar nebula. Thermal evolution, which induces various physicochemical reactions such as aqueous alteration, thermal metamorphism, and volcanism, is important for the evolution of planets. The temperature history inside the planetesimals followed in thermal evolution can vary greatly depending on when and how large they agglomerate and effective thermal conductivity. Therefore, it is essential for the theory of planetary system formation to know the thermal conductivity of asteroids and meteorites, especially those that are thought to have existed since the early stages of planetary system formation.

The Ryugu sample brought back in 2020 by Hayabusa2 was found to be a primitive Ivuna-type carbonaceous chondrite, which is close to the average composition of the Solar System [1]. Although it is expected that the physical properties of Ryugu, including thermal conductivity, will be analyzed in detail, most of the measurements of physical properties of meteorites have been performed on relatively easily available ordinary chondrites [2–4], because they require more samples than chemical and petrological evaluations. Therefore, there has been no method that can evaluate thermal conductivity of limited amount of samples such as Ryugu samples. In this study, we developed a lock-in thermography (LIT) periodic heating method that can measure the thermal diffusivity of small sample of several mm scale without contact [5]. Then we measured the anisotropic distribution of thermal diffusivity for five types of Ryugu samples. Additionally, Thermal inertia was evaluated using reported density and specific heat and compared with values reported for other carbonaceous chondrites.

Samples and Methodology: In this study, six samples of C0002-plate 3, C0002-plate 4, C0025, C0033, A0026 and A0064 were evaluated. C0002-plate 3 and C0002-plate 4 are flat plates cut out from C0002, and the others have granular shape. A spot on the sample is periodically heated using a laser and the temperature response is measured by LIT to obtain the phase lag distribution on the sample surface. The thermal diffusivity is analyzed from the gradient of the phase lag according to this equation; $D = \pi f / (d\theta/dr)^2$. Here, D is thermal diffusivity, f is heating frequency, θ is phase lag and r is distance from heating point. Thermal inertia, which is expressed as the product of the square root of thermal diffusivity, density, and specific heat, was evaluated based on the reported density and specific heat. The heating frequency was selected according to the sample size to avoid the influence of reflected temperature waves at the sample edge, and then measurements were performed at 2, 1, 4, 4, 4, and 20 Hz for C0002-plate 3, C0002-plate 4, C0025, A0026, C0033, and A0064, respectively. C0002-plate 3, C0002-plate 4 and A0064 were measured under vacuum, and C0025, A0026, and C0033 were measured under atmospheric pressure because the vacuum environment was not available at that time yet. C0002-plate 4 was also measured under atmospheric pressure.

Results and Discussion: Figure 1 shows the phase lag distribution and the thermal diffusivity distribution of C0002-plate 3 as a representative of all samples. And the mean, maximum, minimum, and maximum to minimum ratio of the thermal diffusivity distribution for each sample are summarized in Table 1. C0002-plate 3 is known to have cracks in the evaluation region (in the direction of 105-195 deg), and it can be seen that the thermal diffusivity decreases significantly in the direction of the cracks. The other samples also show various thermal anisotropy. The results of C0002-plate 4 measured under both vacuum and atmospheric pressure show that the thermal diffusivity becomes larger, and the thermal anisotropy becomes smaller under atmospheric pressure. The thermal anisotropy seems to be caused by cracks inside the sample. Heterogeneity of mineral composition or microporosity may also affect. The returned Ryugu samples were found to have various mineral compositions and conglomerate-like structures [6].

Table 1. Measurement results of thermal diffusivity.

Sample	Average, mm^2/s	Max/ Min, mm^2/s	Max/Min ratio
C0002-3	0.28 ± 0.07	0.75/ 0.02	38.0
C0002-4 (Vacuum)	0.33 ± 0.08	1.05/ 0.07	15.0
C0002-4 (1 atm)	0.45 ± 0.12	0.60/ 0.31	1.94
C0025	0.56 ± 0.10	1.12/ 0.36	3.11
A0026	0.51 ± 0.02	0.60/ 0.34	1.76
C0033	0.58 ± 0.11	0.82/ 0.27	2.96

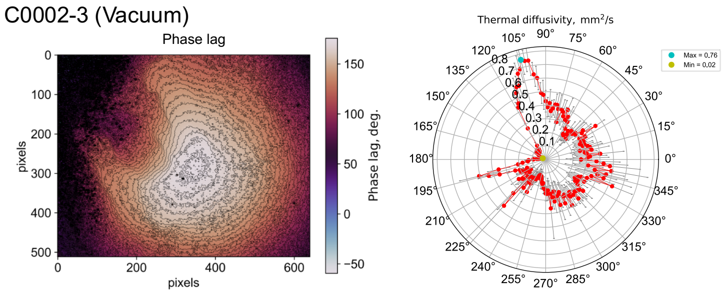

Figure 1. Phase lag and thermal diffusivity distribution of C0002-plate 3.

The obtained thermal diffusivity was then converted to thermal inertia using specific heat and bulk density, and a plot of the relationship with bulk density is shown in Figure 2. Error bars for thermal inertia indicate maximum and minimum values. The bulk densities of these samples are 1820, 1740, 1650, 2260, and 1870 kg/m^3 respectively, and the specific heat of 865 J/(kg·K) measured in the initial analysis was used as a representative value [6]. In addition, Figure 2 also shows plots of the thermal inertia of carbonaceous chondrites reported so far (Cold Bokkeveld (CM2), Jbilet Winselwan (CM2), Murchison (CM2), Murray (CM2), NWA 7309 (CM2), NWA 5515 (CK4), Allende (CV3), Kainsaz (CO3.2)) [4, 7]. The plots are shown in light blue for the measurements taken in vacuum and in purple for those taken at atmospheric pressure. The thermal inertia at atmospheric pressure becomes larger than that at vacuum pressure because the thermal diffusivity becomes larger due to the air-filled cracks.

The averaged values of the thermal inertia of 748-1475 $J/(s^{1/2}m^2K)$ obtained in this measurement is significantly larger than that observed value of 300±100 $J/(s^{1/2}m^2K)$ [8] by the thermal infrared imager (TIR) onboard Hayabusa2. On the other hand, some of the minimum values corresponded to the observed values. This suggests that the value of thermal inertia may differ depending on the measurement scale. In this measurement, the thermal diffusivity was evaluated in the region of several hundreds of micrometers long as thermal diffusion length, but the TIR observations were made at depths down to several centimeters because the thermal inertia was analyzed using the diurnal variation of the surface temperature due to the 7.6-hour rotation period of asteroid Ryugu. Therefore, it is possible that large-scale cracks caused by meteor impacts and thermal stresses on a scale larger than several hundreds of micrometers are widely developed in the rocks and boulders of Ryugu

The Ryugu sample seems to be the lowest-density category when compared to carbonaceous meteorites, and the thermal inertia values appear to follow a correlation trend with the bulk density of carbonaceous chondrites. However, if the bulk density of the Ryugu sample were 2236 kg/m^3, which is the average of the five CM2 densities, the average thermal inertia of the Ryugu sample would be 1132 $J/(s^{1/2}m^2K)$, which is almost identical to the average CM2 value of 1191 $J/(s^{1/2}m^2K)$. This means that the only substantial difference between Ryugu and CM2 is the bulk density, and the product of thermal conductivity and specific heat are almost the same. Since the thermal conductivity generally decreases when the bulk density decreases due to porosity, it is possible that the thermal conductivity of Ryugu's matrix is larger than that of CM2. Further validation will be conducted by evaluating additional carbonaceous chondrites including CI chondrites, which are closest to Ryugu.

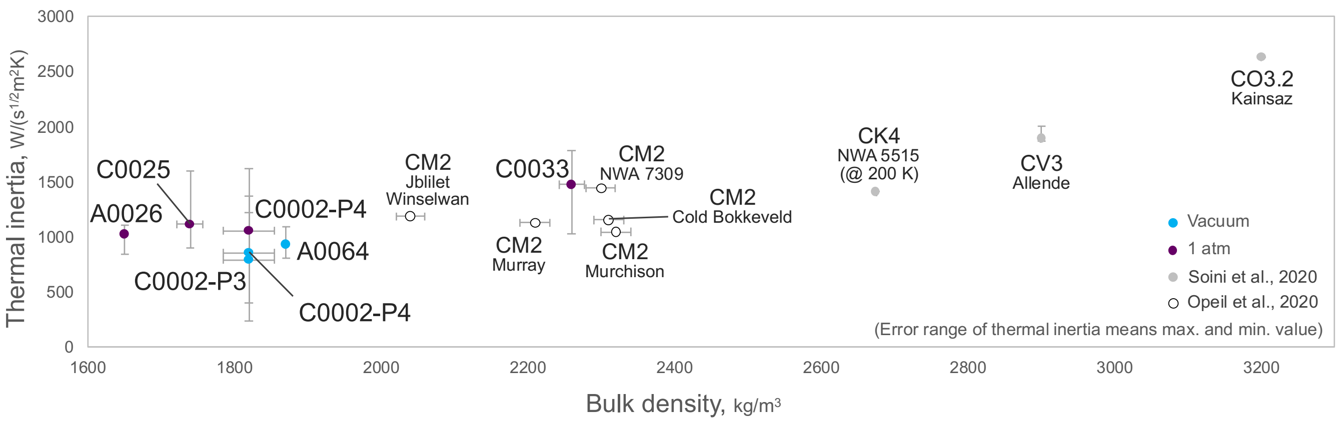

Figure 2. Thermal inertia vs. bulk density of Ryugu samples and carbonaceous chondrites.

References

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