AN EXPERIMENTAL STUDY OF EXCAVATION FLOW IN IMPACT CRATERING. S. Yamamoto[1], N. Okabe[1], and T. Matsui[1], [1]Graduate School of Frontier Sciences, University of Tokyo, Tokyo 113-0033, Japan (yamachan@gfd-dennou.org).

Introduction: Impact craters have been considered to be formed by two processes: excavation of target material and displacement of target material downward [e.g.1,2]. The amount and region of excavation are important parameters for studies of internal structure and surface evolution of bodies in the solar system. However, there are few experimental data concerning the excavation process. Therefore, we conducted impact cratering experiments to measure the excavation region and amount of the excavated material.

Experiments: Polycarbonate projectiles with mass of 0.49g and diameter of 10mm were accelerated by a single-stage gas gun. Impact velocities ranged from 54 to 321m/s. The impact angles to target surface were vertical. We prepared soda-lime glass spheres with mean sizes (s) of 40, 80, and 220μm as the target. The bulk densities (ρ) of the targets with s=40, 80, and 220μm are 1.56, 1.53, and 1.49g/cm^3, respectively. The target glass spheres were placed in a stainless container (20×33×9.0cm) in the vacuum chamber with the ambient pressure < 100 Pa.

We measured the amount of the excavated material as follows: The stainless container was covered by a board with a centered hole. When a projectile impacts at the center of the hole, ejecta are thrown out through the hole (Fig.1a). After experiments, we collected the ejecta on the board and measured its mass. We used five boards with different hole radii (r=2.9, 3.5, 4.0, 4.5, and 5.0 cm).

In this method, we need to know the hole radius r which is coincident with the transient crater radius R. However, it is difficult to satisfy the condition r=R exactly. Thus, we conducted many impact experiments by changing the impact velocity v. Figure 1(a)-(c) show schematic illustration of the relation between v and the ejecta. At lower velocity (R<r), it is expected that the collected ejecta mass increases with increase in v (Fig.1a). At a certain velocity, r satisfies the condition r=R and the ejecta on the board corresponds to total ejecta mass (Fig.1b). At higher velocity (R>r), only the target materials inside the hole are ejected (=constant ejecta mass marked by the arrow in Fig.1d). In this case, it is expected that the collected ejecta mass becomes independent of v.

In Figure 1d, the collected ejecta mass M is plotted against v. We can see that M increases with v at lower velocity, but M is independent of v at higher velocity (v>200m/s). Thus, from this figure, we can estimate the amount of the excavated material.

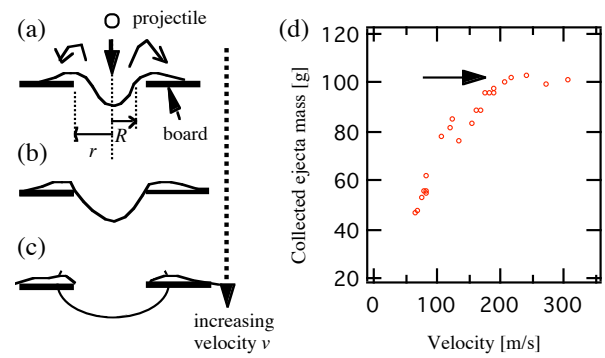

Figure 1: (a-c) Schematic illustration of the relation between impact velocity and the ejecta on the board. Solid curve represents the cross section of the transient crater. (d) Ejecta mass on the board is plotted against impact velocity. This is the case for s=200μm and r= 5.0cm.

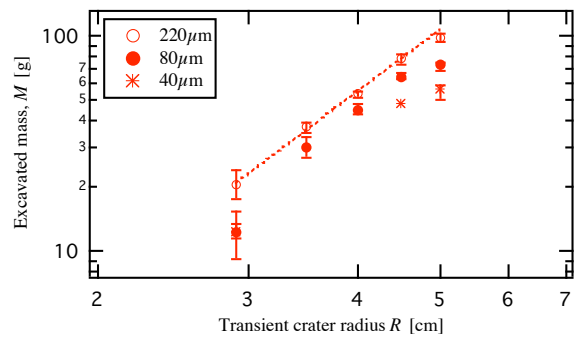

Figure 2: Mass of the excavated material is plotted against transient crater radius. Dashed line indicates the best-fit curve for s=220μm.

Results: (1) mass of excavated material. In Figure 2, the mass of excavated material M is plotted against transient crater radius R. We can see clearly that M increases with increase in R exponentially. For s=220μm, the least square-fit gives the relation of M $R^{3.0}$. This means that M is proportional to the transient crater volume V_{tr}. The exponents of power law for s=80 and 40μm were 3.4, and 2.9, respectively. The masses of excavated material for s=80 and 40μm are also nearly proportional to V_{tr}.

(2) Volume ratio of excavation region to transient crater cavity. Next, we compare the volume V_{ex} of excavation region with transient crater cavity volume. We defined the volume of the excavation region by V_{ex}=M/ρ, where ρ is the bulk density of the target.

In order to estimate the volume of transient crater cavity, we performed another impact experiments under

the same condition but no board. By using a camcorder, we observed formation processes of transient crater. From the analysis of images taken by the camcorder, we can determine a transient crater radius R as a function of v. It was difficult to measure transient crater depths H from the images. Thus, a penetration depth of a projectile was assumed to be the transient crater depth H.

It was also difficult to know the shape of transient crater from the images. We assumed ellipsoidal and parabolic shapes as the transient crater shape. For the case of ellipsoidal shape, the crater volume V_{tr1} is given by $V_{tr1} = 2\pi R^2 H/3$ and, for the case of parabolic shape, the crater volume V_{tr2} is given by $V_{tr2} = \pi R^2 H/2$. The transient crater volume V_{tr} was defined by $V_{tr} = (V_{tr1} + V_{tr2})/2$, and V_{tr1} and V_{tr2} were regarded as the maximum and minimum estimates, respectively.

In Figure 3, the volume ratio V_{ex}/V_{tr} is plotted against R. We can see clearly that the volume ratio is independent of R. Figure 3 also shows that the volume ratio decreases with decrease in s. The mean values of V_{ex}/V_{tr} for s=220, 80, and 40μm are 0.36, 0.27, and 0.18, respectively.

(3) Depth ratio of excavation region to transient crater cavity. Next, we compare the depth d of the excavation region with the transient crater depth H. We estimated the depths of the excavation region as follows: We assumed ellipsoidal and parabolic shapes for the excavation region. For the case of ellipsoidal shape, the maximum depth d_1 is given by d_1=4 $V_{ex}/\pi R^2$ and, for the case of parabolic shape, the depth d_2 is d_2=3 $V_{ex}/2\pi R$. We defined the depth d by $d=(d_1+d_2)/2$, and d_1 and d_2 were regarded as the minimum and maximum estimates, respectively. In Figure 4, the depth ratio d/H is plotted against R. It is clear from this figure that the depth ratio is independent of R. Figure 4 also shows that the depth ratio decreases with decrease in s. The mean values of d/H for s=220, 80, and 40μm were 0.28, 0.21 and 0.14, respectively.

Discussion: According to the Maxwell Z-model, the volume ratio of excavation region to transient crater is expressed by $Z = (2 + V_{ex}/V_{tr})/(1 - V_{ex}/V_{tr})$, where Z is a nondimensional parameter [2,3]. Using the results shown in Fig.3, we can estimate Z=3.7, 3.1, and 2.7 for the results for s=220, 80, and 40μm, respectively. In the Maxwell Z-model, the excavation flow depth increases with increase in Z [2]. Thus, this result suggests that the excavation flow pattern depends on grain sizes; the excavation flow for smaller grains was relatively shallower than that of larger grains.

This observation might be interpreted as follows: The porosity of the target increases with decrease in s (the porosity for s=220, 80, and 50μm were 0.38, 0.39, and 0.40, respectively). In addition, the penetration depths of the projectiles for s=40 and 80μm are shallower than those for s=220μm. These facts may suggest that the smaller grains retain larger cohesion (friction) among the grains. The cohesion (or friction) might affect the depth of effective origin of flow; the depth of effective origin of flow may decrease with increase in cohesion (or friction). If so, the depth of effective origin of flow would decrease with decrease in grain size. This might be the reason why the excavation flows for smaller grains are shallower than those for larger grains.

Summary: We measured the volume and depth ratios of excavation region to transient craters for the glass spheres with different sizes. While the volume and depth ratios were independent of transient crater radius, the volume and depth ratios showed to decrease with decrease in grain sizes. The present results may suggest that excavation flow pattern depends on grain sizes.

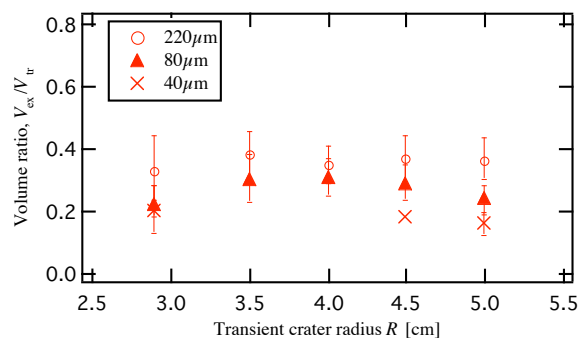

Figure 3: Volume ratio of the excavation region to the transient crater cavity is plotted against the transient crater radius.

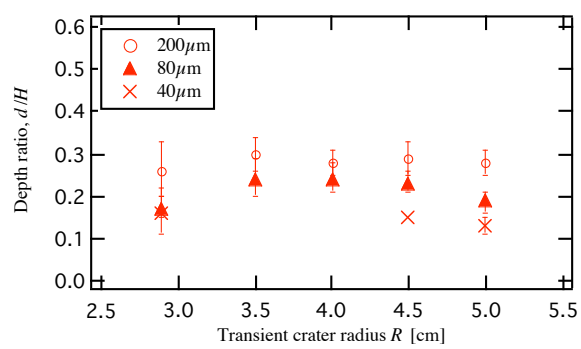

Figure 4: Depth ratio of the excavation region to the transient crater cavity is plotted against the transient crater radius.

References: [1] Hörz, F. *et al.*, (1991) *In Lunarsource book (Heiken G.H. et al. eds.)*, 61-120. [2] Melosh H.J. (1989) *Impact cratering*, Oxford Univ. Press. [3] Maxwell, D.E. (1977) *In Impact & Explosion cratering (Roddy D.J. et al. eds)*, Pergamon press, 1003-1008.