DIRECT OBSERVATION OF TRANSIENT CRATER GROWTH

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ABSTRACT

We observed the formation and collapse processes of transient crater using the laser method. Polycarbonate projectiles, which were accelerated by a single-stage light-gas gun, were impacted vertically into soda-lime glass sphere targets with different material properties. We found that the increase in crater diameter during the excavation stage does not follow a simple power-law relation and its increase rate depends on target material properties. We also showed that the transient crater collapses owing to the gravity, resulting in increase in diameter and decrease in depth. The degree of collapse also depends on target material properties. These results suggest reconsideration of scaling relations on impact cratering.

1. INTRODUCTION

Scaling relations on impact cratering in the gravity regime have been studied for many years, based on explosion and impact experiments for granular targets [e.g., 1, 2, 3, 4]. However, even for the gravity regime, the impact cratering may be affected by target material properties [e.g., 5, 6, 7]. Thus we need to take into account the effects of target material properties on scaling relations in the gravity regime. However, little is known as to how the scaling relations are related to target material properties. This is because the previous scaling relations were formulated based on the data of final craters. In order to investigate this issue, we need to study the relation between transient crater growth (i.e. formation and collapse processes of transient craters) and target material properties. In this case, direct observation of transient crater growth is necessary.

In the previous works, the quarter-space technique has been used for direct observation of transient crater growth [e.g., 3, 7, 8, 9]. In this method, a granular target or sand target is set in a sample box with a transparent window, and a projectile is impacted into the target along the transparent window, through which we can observe the cross sectional view of transient crater growth. However, the presence of the transparent window may affect transient crater growth. Indeed, it has been reported that the crater diameters of final craters measured in the quarter-space technique are smaller than those in the half space experiment [e.g., 8]. Thus, for the quantitative study of transient crater growth, we need to develop another way of direct observation without any physical interference with targets.

We have recently developed a new technique of the direct observation using a laser sheet [10] (we call this method the laser method and describe in detail hereafter). This allows us to observe the transient crater growth without any physical interference with targets. In this study, using the laser method, we did the direct observations of transient crater growth for different target materials, and studied the relation between transient crater growth and target material properties.

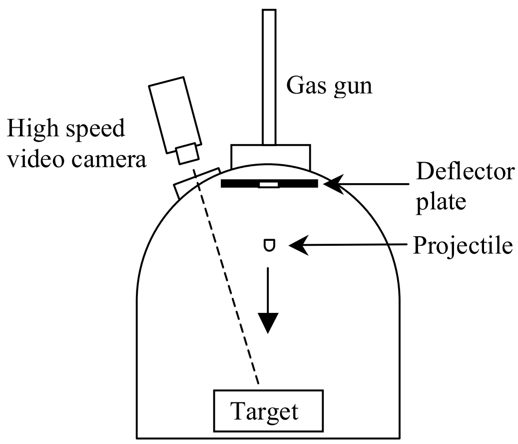

Fig. 1: Schematic diagram (side view) of the experimental apparatus.

2. EXPERIMENTAL SETUP

A schematic diagram of the experimental apparatus is shown in Fig. 1. We used a polycarbonate cylinder with a hemispherical front as projectile (10 mm diameter, 8 mm length, and mass of 0.49 g). The projectile was accelerated by a single-stage light-gas gun. The impact velocities ranged from 93 to 236 m/s (Table 1). The impact angle was vertical to the target surface. We prepared soda-lime glass spheres as targets, whose mean diameters are 36 and 220μm, respectively; these are referred as TA and TC targets hereafter. In Table 2 we list the target properties such as porosity and the angle of repose. Although the target materials are the same, their target material properties are different between TA and TC targets, because the mean diameters are different (the porosity and the angle of repose depend on the mean grain size [7]). A stainless basin (40 cm diameter and 15 cm depth) filled with the glass spheres was placed in the vacuum chamber (1 m diameter and ~1.3 m height)(Fig. 1). All the experiments were conducted under the condition with the ambient pressure < 50 Pa. In order to prevent the propellant gas (helium) from perturbing the impact cratering, a deflector plate (with a hole 18 mm in diameter for the passage of projectiles) was set at a projectile inlet of the experimental chamber (Fig. 1). Experimental conditions are summarized in Table 1.

Table 1: Experimental condition.

Shot No.	Target	Impact velocity [m/s]
604091	TA	189
604092	TA	236
604093	TA	100
604114	TA	216
604117	TA	205
6041110	TA	96
604051	TC	98
604052	TC	205
604053	TC	93
604054	TC	160
604055	TC	216

Table 2: Material properties of the glass sphere targets.

Target	TA	TC
Mean diameter	36μm	220μm
Porosity	40 %	36 %
Angle or repose	33 deg	25 deg

3. LASER METHOD

Fig. 2 shows a schematic diagram of the laser method. A vertical laser-sheet formed by a 3mW He-Ne laser through a cylindrical lens was used to illuminate the impact site of a projectile. The temporal change of the laser line formed on the target surface during the transient crater growth can be observed by using a high-speed video camera set above the target (Fig. 2). Example images taken by the camera are shown in Fig. 3. This is the case for impact velocity of 216 m/s into TC target. Before impact (Fig. 3a), we see a straight laser line on the target surface. After impact, the shape of the laser line changes with the expansion of the crater cavity (Fig. 3b). Transient crater was formed by t=0.108 s, because the crater rims can be seen by this time step (white arrows in Fig. 3c). Then, the transient crater started to collapse and the crater shape began to change again. Finally, the collapse halts and then the final crater was formed (Fig. 3d).

Analyzing images taken by the camera (the detailed analytical procedure is described in [10]), we obtained the profile of the crater cavity for each image (Fig. 4). From these profiles, we can determine the apparent diameter and depth of the crater cavity for each time step.

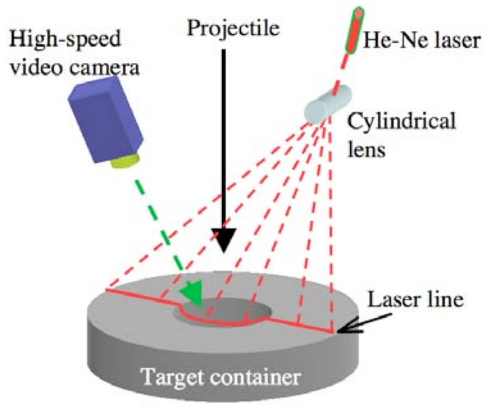

Fig. 2: Schematic illustration of the laser method.

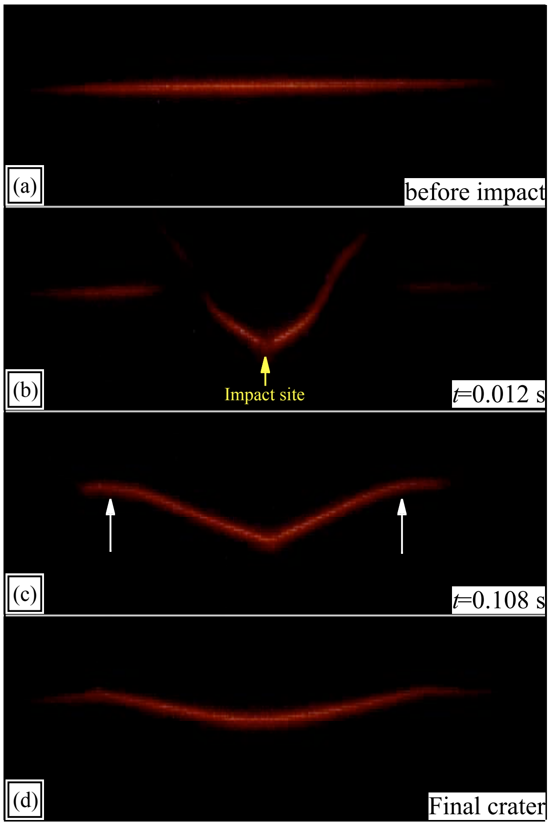

Fig. 3: Example images taken by the camera. t is the time after impact. This is the case for impact velocity of 216 m/s into TC target (Shot 604055).

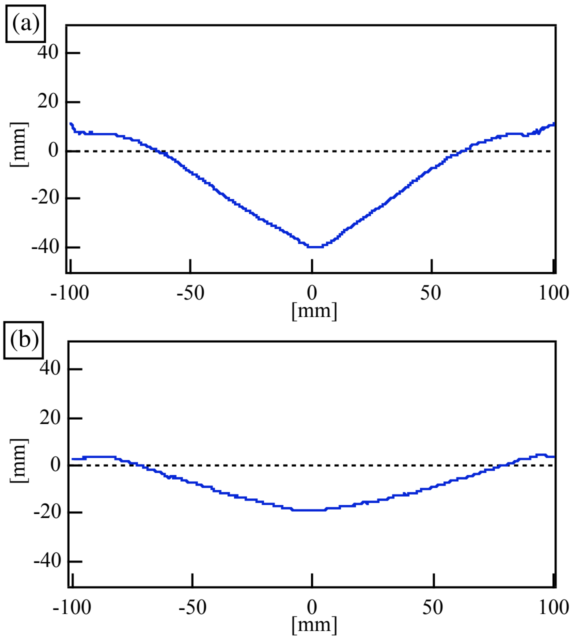

Fig. 4: Example profiles of the crater cavities at (a) t=0.108 s and (b) t=0.264 s, respectively. This is the case for impact velocity of 216 m/s into TC target (Shot 604055). The broken line corresponds to the original target surface before impact.

4. RESULTS: TEMPORAL CHANGES IN DIAMETER AND DEPTH

Using the laser method, we can observe the temporal changes in diameter and depth for various impact velocities for TA and TC targets. Fig. 5 shows the temporal changes in diameter (red solid circles) and depth (blue solid circles) for the case of the impact with velocity of 216 m/s into TC target. As shown clearly in this figure, the diameter increases with increasing time t after impact. We consider that the transient crater is formed by t~0.108 s, because the crater rim is formed by this time step (Fig. 3c). In this case, the diameter of transient crater is 129 mm. The increase rate in crater diameter appears to become slow but after formation of transient crater, the diameter starts to increase again owing to the collapse of the crater wall and rims. The increase in diameter stops at around t~0.2 s, and we consider that the final crater was formed at this time step, that is, the diameter does not change further. The final crater diameter is 152 mm in this case.

As shown in Fig. 5 the depth (blue circles) rapidly increases until about t=0.008 s after impact. However, the increase in depth becomes slow after this time step and stops at around t~0.012s. Then the depth becomes to decrease slightly and to be nearly constant until t~0.1s, which is nearly equal to the formation time of transient crater. After t~0.1s, the depth starts to decrease largely owing to the collapse of the crater. Finally, the collapse halts by t~0.3s, because the depth does not change further after this time step. The depth of final crater is 19 mm.

Note that the increase rate in diameter does not follow a power-law relation, as shown in Fig. 5; the increase rate gradually decreases with increasing t even during the formation processes of transient crater (t<~0.1 s). This feature such as the gradual increase in diameter is different from the previous result observed by the quarter-space technique [e.g., 3], in which the increase rate in diameter during the early stages (t<~0.004 s) of formation process of transient craters was shown to follow a simple power-law relation ([3] did not show the features for $t > 0.004$ s). The reason for this discrepancy is uncertain, but may be due to the difference between the early and late stages of formation process of transient craters. In any case, the present results may suggest that we need to take into account this feature (the gradual increase) when we consider the scaling relations on crater diameters.

Furthermore, as shown in Fig. 5, the increase in diameter continues after the increase in depth stops at t~0.012 s, which means that the radial expansion process continues after the vertical expansion process stops. It is therefore suggested that the shape of the crater cavity changes with time: the expansion of the crater cavity does not follow a self-similar way.

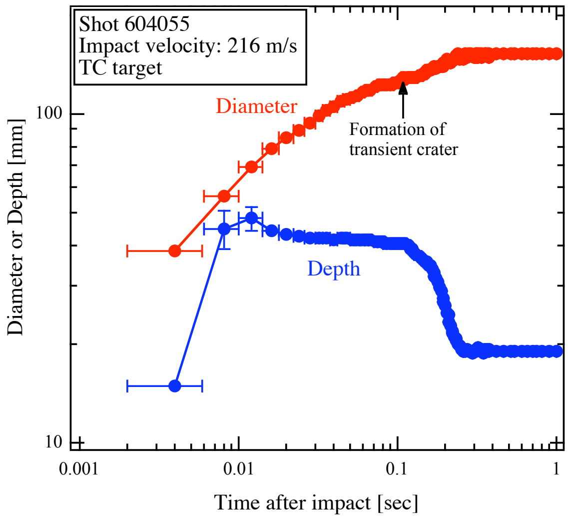

Fig. 5: Temporal changes in diameter and depth for impact velocity of 216 m/s into TC target.

5. EFFECTS OF TARGET MATERIAL PROPERTIES ON TRANSIENT CRATER GROWTH

5.1 Formation process

In order to investigate how the formation process of transient craters depends on the target material properties, we first compared the results of TA and TC targets for the same impact velocity. In Fig. 6, the diameter of crater cavity is plotted against the time after impact for TA and TC targets (the impact velocities for both cases are 205 m/s). At the early stage (t<~0.008 s), we cannot see any significant differences in diameter between TA and TC targets. This may suggest that the effects of target material properties are not important during this stage. On the other hand, at later stages (t >~0.008 s) we can see the difference between TA and TC targets; the diameters for TC target are larger than those for TA target for t >~0.008 s, and this difference increases with increasing t. It is therefore suggested that the formation process of transient craters depends on target material properties at the later stage.

This might be interpreted as follows: During the early stage of the formation processes (t<~0.008 s), the dynamic pressure of the excavation flow was high enough to dominate over the effects of target material properties. Therefore, the formation process does not depend on target material properties at the early stage. On the other hand, the dynamic pressure of the excavation flow becomes to be low at the later stage of the formation processes, and as a result the excavation flow during the later stage was affected by the material properties such as internal friction or cohesion among glass spheres.

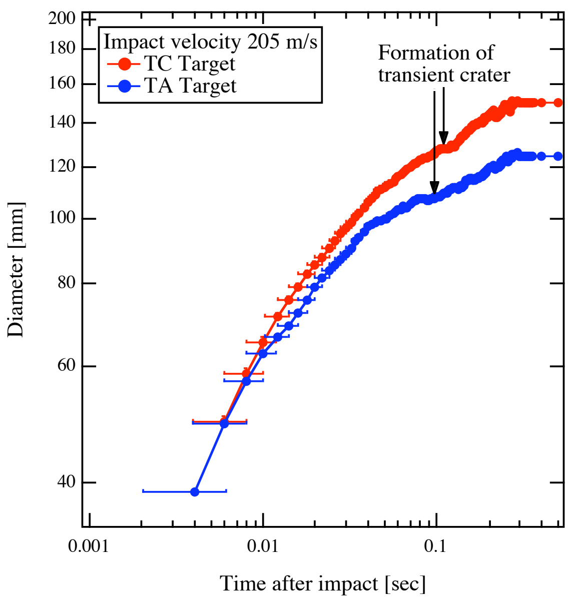

Fig. 6: Diameter growth for TA and TC targets (Shots 604117 and 604052 for TA and TC targets, respectively). The impact velocities for both cases are the same (205 m/s).

5.2 Collapse process

In order to investigate how the collapse process depends on target material properties, we next estimate the degree of collapse. We use the diameter ratio of final to transient craters as the estimate of the degree of collapse. In Fig. 7, the degrees of collapse are plotted against the impact velocity for TA and TC targets. We can see that the degrees of collapse for TC target are larger than those for TA target; the average values for TC and TA targets are 1.17±0.02 and 1.12±0.01, respectively. It is therefore suggested that the degree of collapse depends on target material properties.

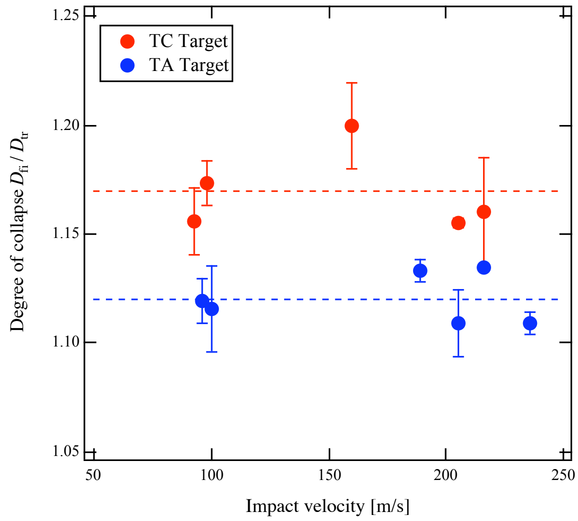

Fig. 7: The diameter ratio of D_{fi} to D_{tr} (the degree of collapse) is plotted against the impact velocity for TA and TC targets, where D_{fi} and D_{tr} are the diameters of final and transient craters, respectively. The broken lines indicate the average values: 1.12 and 1.17 for TA and TC targets, respectively.

5.3 Crater shape: depth-diameter ratio

Next we study the relation between the depth and diameter (depth-diameter ratio) of transient and final craters. In Fig. 8 the depth-diameter ratios of transient and final craters are plotted against the impact velocity for TA and TC targets. We cannot see any systematic difference in the depth-diameter ratio of transient craters (filled circles) between TA and TC targets. On the other hand, it is clear that the depth-diameter ratios of final craters for TA target (blue open circles) are larger than those for TC target (red open circles). The average values of final craters for TA and TC targets are estimated to be about 0.17±0.01 and 0.13±0.01, respectively. Therefore, we may suggest that the crater shape (depth-diameter ratio) of final craters depends on target material properties, while the crater shape of transient craters does not. This may suggest that the shape of final craters is mainly controlled by the collapse process.

6. SUMMARY

We observed the formation and collapse processes of transient crater using the laser method. We found that the increase rate in diameter of crater cavity does not follow a simple power-law relation; the increase rate during the formation process of transient craters decreases with increasing time, and depends on target material properties. In addition, the radial expansion process continues after the vertical expansion process stops, suggesting that the shape of the crater cavity changes with time. We also showed that the transient crater collapses owing to gravity, resulting in increase in diameter and decrease in depth. The degree of collapse was also shown to depend on target material properties. Furthermore, the crater shape (depth-diameter ratio) for final craters showed target material property dependence, while that for transient craters did not. These features may need to be considered, when we consider the effects of target material properties on the scaling relations.

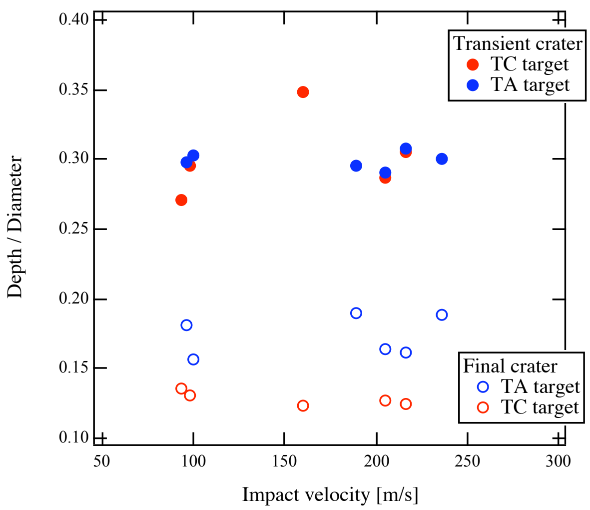

Fig. 8: Depth-diameter ratio of transient (solid circles) and final craters (open circles) for TA and TC targets.

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