DIRECT OBSERVATION OF TRANSIENT CRATER GROWTH IN GRANULAR TARGET

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Introduction: Scaling rules on impact cratering in gravity regime have been studied for many years, based on explosion and impact experiments for granular targets [see, e.g. 1, 2]. However, even for the gravity regime, impact cratering may be affected by target material properties [e.g. 3]. In order to investigate this issue, direct observation of transient crater growth is necessary. We have recently developed the laser method to directly observe transient crater growth [4]. In this study, using the laser method, we observed the transient crater growth for various targets to study how the impact cratering in the gravity regime is affected by target material properties.

Experimental Setup: Polycarbonate projectiles (10 cm in diameter and 0.49 g in mass) were accelerated by a single-stage light-gas gun. The impact angle is vertical to the target surface. We prepared soda-lime glass spheres as targets, whose mean diameters are 36 and 220μm, respectively (hereafter they are referred as TA and TC targets). The target material properties such as the porosity and the angle of repose are different between the two targets [3]. All the experiments were conducted under the condition with the ambient pressure < 50 Pa.

Observation by laser method: In the laser method, a vertical laser-sheet is used to illuminate the target at the impact site, and the temporal change of a laser line on the target surface during the transient crater growth can be observed by a high-speed video camera set above the target [see 4]. Fig. 1 shows an example of images taken by the camera. Before impact (Fig. 1a), we see a straight laser line on the target surface, but after impact (Fig. 1b), the shape of the laser line changes with the expansion of the crater cavity. We define transient crater formation to be t~0.11 s, because the crater rims can be seen at this time (arrows in Fig. 1c). This is a more conservative estimate of transient crater growth than used in from [4] where initiation of kinking in the curtain was used. The reason for using this new definition will become obvious below. After this time, the transient crater starts to collapse and the crater shape begins to change again. Finally, at t~0.3s the collapse halts and the final crater is formed (Fig. 1d). Analyzing these images [see 4], we can measure the apparent diameter of the crater cavity at each time step.

Temporal change in diameter: Fig. 2 shows the temporal changes in diameter. Note that during the transient crater formation process (t<0.11s), the increase in crater diameter does not follow a simple power-law. The data at early times (t<0.03 s) appears to follow the power-law relation (solid line in Fig. 2) but the data at late times (but before the end of transient crater formation) deviates from the power-law relation. This departure from the power-law is different from the previous result observed by the quarter-space technique [5], in which the increase rate in diameter was shown to follow a simple power-law relation, because these studies focused only on earlier times t< 0.004 s [5]. Previous studies have indicate such deviations in the depth growth of crater cavity [e.g. 1, 6], but have never been explicitly detailed for the diameter growth as in this study.

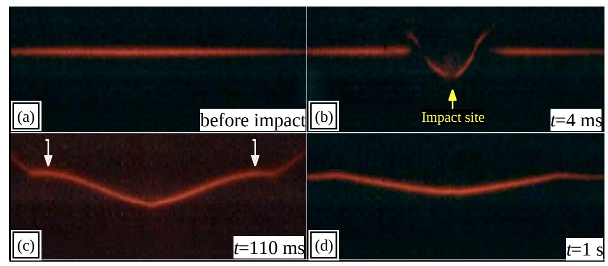

Figure 1: Example images taken by a high speed video camera. t is the time after impact. This is the case for impact velocity of 200 m/s into TC target (Shot 608142).

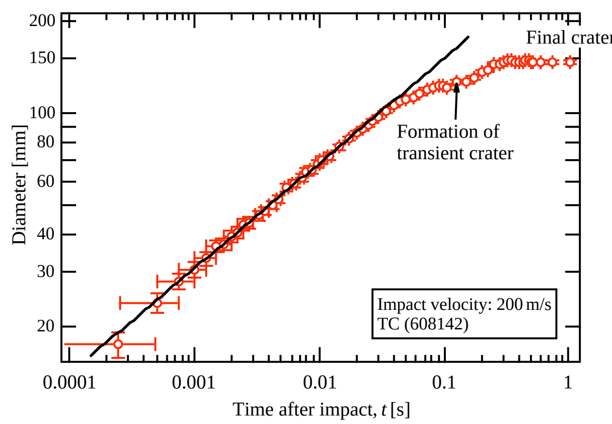

Figure 2: A temporal change in diameter for impact velocity of 200 m/s into TC target. Solid curve is the power-law relation derived from the data at t<0.03 s. The data does not follow the power-law relation at late times but before the end of transient crater formation.

Interpretation: The deviation from a power-law for diameter growth indicates that a more rigorous approach to interpreting crater growth is required. This approach should not be based on a power-law. We propose to modify Maxwell's Z-Model [7]. In the original version of this model, the radial component of the excavation flow velocity u_r at the distance r is given as $u_r=\alpha(t)/r^Z$, where Z is a constant and $\alpha(t)$ is a function of the time t. If $\alpha(t)$

is assumed to be a constant, the diameter $r(t)$ of the crater cavity at t is given as $r(t) \propto t^{1/(Z+1)}$ (that is, a simple power-law relation)[7]. On the other hand, we found that $r(t)$ does not follow a simple power-law relation. Thus, instead of the constant $\alpha(t)$, we assume $\alpha(t) \propto e^{-Bt}$, which means that the velocity magnitude of the excavation flow decreases exponentially with t, where B is a decay constant. In this case, the diameter $r(t)$ can be derived as

$$r(t) \propto (1-e^{-Bt})^{C}, \quad \ldots (1)$$

where a power-law exponent C is $C=1/(Z+1)$. In Fig. 3, using the least-square fit, we compared the experimental results for TA and TC targets with Eq. (1). It is clearly shown that the data for TA and TC targets are well fitted by Eq. (1) (solid curves). Thus, the diameter growth in the formation process can be represented by Eq. (1).

We next investigate how the coefficients B and C in Eq. (1) depend on target material properties. We did impact experiments for various impact velocities v_i for TA and TC targets, and determined B and C using the least-squares fit. In Fig. 4a, the decay constant B is plotted against v_i for TA and TC targets. It is clearly shown that the values of B for TA target are larger than those for TC target. The average values (broken lines) for TA and TC targets are 22.2±1.8 and 17.1±0.9, respectively. This may suggest that the decay rate in the velocity magnitude of the excavation flow differs between the two targets. In Fig. 4b, the power-law exponent C is plotted against v_i. We see that the values of C for TC target are slightly larger than those for TA target. The average values (broken lines) of C for TA and TC targets are 0.341 ± 0.007 and 0.358 ± 0.007, respectively. Thus, the value of C (and $Z=-1+1/C$) also differs between the two targets.

The differences in B and C between TA and TC may be due to the differences in target material properties. Previous studies [e.g. 2, 3] have suggested that internal friction and/or porosity in target materials affect the transient crater growth. The internal friction (which is related to the angle of repose) and porosity are different between TA and TC targets: the angles of repose are 33 and 25 deg, respectively, and the porosities are 40 and 36%, respectively [3].

Summary: We observed the transient crater growth using the laser method, and found that the increase rate in diameter of crater cavity for the formation process of transient crater does not follow a simple power-law relation. This feature can be represented by Eq. (1), which means that the velocity magnitude of the excavation flow decreases exponentially with t. The values of B and C in Eq. (1) were shown to depend on target material properties. These features may need to be considered when we consider the effects of target material properties on scaling rules.

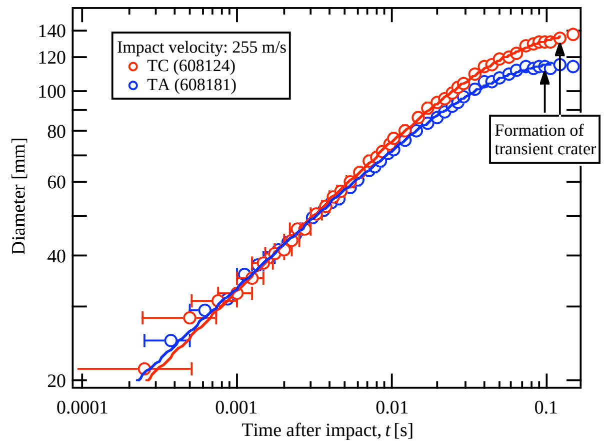

Figure 3: Temporal changes in diameter for TA and TC targets. The impact velocities are 255 m/s. Solid curves are best-fit ones by Eq. (1).

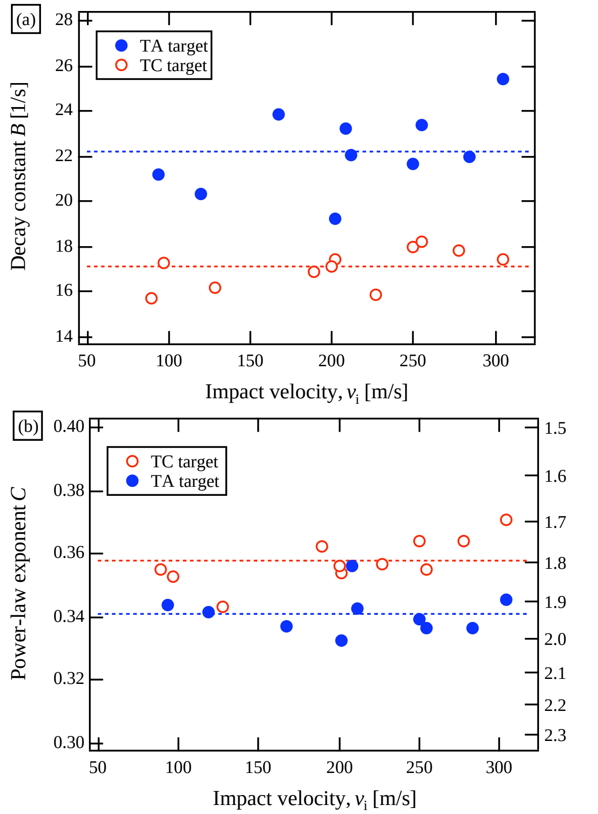

Figure 4: (a) The decay constant B and (b) the power-law exponent C for TA and TC targets. The right axis in (b) indicates the Z value ($Z=-1+1/C$). The broken line is the average value for each target.

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