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Impact experiments on highly porous targets: Cavity morphology and disruption thresholds in the strength regime

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ABSTRACT

Small bodies were probably very porous during the formation of the solar system. To understand the evolution of such bodies, impact experiments on sintered glass-bead targets with porosities of 80%, 87%, and 94% were performed at velocities of 1.8–7.2 km s^{-1} using various projectiles with densities ranging from 1.1 g cm^{-3} to 4.5 g cm^{-3}. Here we report on the resulting cavity morphologies formed by these impacts, with particular attention paid to the depth from the cavity's entrance hole to its maximum diameter, the entrance-hole diameter, and the maximum diameter. We obtained empirical relations of the entrance-hole diameter and the maximum diameter using non-dimensional parameters for crater scaling. We also report on the targets' disruption thresholds, Q^*. Each Q^* value is on the order of kilojoules per kilogram, which is higher than the equivalent values for pure ice targets and basalt targets determined from high-velocity impact experiments. Non-dimensional disruption thresholds, $\rho_t Q^*/Y$, where ρ_t and Y are the targets' bulk densities and compressive strengths, respectively, are calculated for various targets including those used in this study; they are shown to be within approximately one order of magnitude for a given porosity, although the impact velocities and target sizes range from 1 m s^{-1} to 7.2 km s^{-1} and from 2 cm to 14 cm, respectively. The previous proposed strength parameter for the catastrophic disruption threshold, $\Pi_s{}^*$, is also calculated. It is shown to be roughly constant, irrespective of porosity if we assume that the scaling parameter μ decreases linearly with increasing porosity.
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1. Introduction

During the early formation phases of the solar system, small bodies were probably characterized by very high porosities. Although these bodies somehow lost their high porosities through processes such as compaction caused by collisions, disk-gas pressure, self-gravity (Kataoka et al., 2013), and/or sintering (Yomogida and Matsui, 1984), some are estimated to still have high porosities of up to 86% (Consolmagno et al., 2008). Collisions of bodies characterized by different bulk densities and strengths may have occurred owing to the migration of giant planets. The Grand Tack model (Walsh et al., 2012) suggests that both inner- and outer-orbit bodies were scattered and mixed following the inward and outward migrations of Jupiter and Saturn. The Nice model also implies that Kuiper Belt Objects were scattered and transported to the asteroid region when Jupiter and Saturn crossed their 1:2 mean-motion resonance (Gomes et al., 2005).

Previous laboratory experiments in the strength regime have shown that porosity and strength affect the outcome of a collision. Love et al. (1993) and Michikami et al. (2007) used sintered glass-bead targets with porosities of up to 60% and 80%, respectively, and showed that the crater depths increased with increasing porosity of the target. Ryan et al. (1999) showed that the disruption threshold, Q^* (described in Section 3.2), for pure ice targets is smaller than those for silicate and metal targets. Setoh et al. (2010) used sintered glass-bead targets of ~40% porosity and various compressive strengths, and showed that Q^* increased with increasing target compressive strength. Love et al. (1993) indicated that the Q^* of sintered glass-bead targets increased with increasing target porosity.

To understand the collisional evolution of highly porous bodies, it is necessary to understand the impact characteristics of targets with porosities in excess of those used in previous studies. In this study, impact experiments on sintered glass-bead targets with different porosities of up to 94% are conducted. The cavity morphologies and disruption thresholds of the high-porosity targets are analyzed. The results are compared with previous studies of porous targets of various materials.

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2. Experiments

We prepared sintered hollow glass beads targets with porosities, ϕ, of 87% and 94%, which we refer to as fluffy87 and fluffy94, respectively. Normal, solid glass-bead targets with a porosity of 80% were also prepared ("fluffy80"). These sintered glass-bead targets were cylindrical shape. Table 1 includes a summary of the target properties; target dimensions are listed in Tables 2 and 3. Uniaxial compressive strengths of the targets were measured using a compressive testing machine at Kobe University (Japan). The details of target preparation and strength measurement are described in Okamoto et al. (2013).

Impact experiments were conducted using a two-stage light-gas gun at the Institute of Space and Astronautical Science (ISAS), Japan. A split-type nylon sabot (Kawai et al., 2010) was used to accelerate different types of projectiles. The projectiles were titanium (4.5 g cm^{-3}), aluminum (2.7 g cm^{-3}) and nylon (1.1 g cm^{-3}) spheres with diameters of 1 mm or 3.2 mm and basalt (2.7 g cm^{-3}) cylinders with a diameter of 3.2 mm and height of 2 mm. The impact velocities ranged from 1.8 to 7.2 km s^{-1}. Tables 2 and 3 summarize the conditions of the cavity-formation and target-disruption experiments, respectively. Note that we used targets of different aspect ratios (i.e., different diameter-to-height ratios), to examine the effect of the target shape on the degree of disruption. The targets were recovered after the shots, and the mass of the largest fragment was determined if the target had been disrupted. The track profiles of non-disrupted targets were observed and analyzed using transmission images obtained with a micro-X-ray tomography instrument (ELE-SCAN NX-NCP-C80-I (4); Nittetsu Elex Co.) at Kyoto University, Japan (Tsuchiyama et al., 2002). The results of the experiments are also presented in Tables 2 and 3.

3. Results and discussions

3.1. Cavity shape

3.1.1. Track profile and drag coefficient

Fig. 1 shows some track profiles extending from the entrance hole to the end of the track. Note that the tracks' X-ray images are shown in Figure 2 of our previous study (Okamoto et al., 2013). The track shape could be divided into two types: an elongated "carrot" shape and a short "bulb" shape. A distinction of these two types for the targets was the same criteria as that for aerogel targets (Burchell et al., 2008), that is the ratio of the maximum diameter to the projectile's penetration depth was 0.11, although transitional shapes between the carrot and bulb shapes exists. The track shape depends on the ratio of the projectile's dynamic pressure to its strength (Okamoto et al., 2013). In this study, we focus on the bulb-shaped tracks, in particular on the cavity shape. Fig. 2 presents an example of an X-ray transmission image and a sketch of a cavity cross section. The bulb-shaped cavity is characterized by an entrance hole with a diameter of several times the projectile diameter and a maximum cavity diameter located at some depth from the entrance hole. These characteristics of the bulb-shaped cavity have previously also been found in very porous targets such as aerogel and foamed polystyrene (Hörz et al., 2006; Ishibashi et al., 1990).

Previous studies (Niimi et al., 2011; Okamoto et al., 2013) have reported that projectiles decelerate in the target through both inertial drag and drag that is proportional to the target strength. It has been shown that the former dominates during most of the penetration process, while the latter is effective only in the final phase of a projectile's penetration. The equation of motion for a given projectile is thus given by

$$m_p \frac{dv}{dt} = -\frac{1}{2} C_d \rho_t S v^2, \tag{1}$$

where m_p, v, and C_d are the projectile mass, velocity, and drag coefficient, and ρ_t, and S are the target's bulk density and the projectile's cross-section area, respectively. The penetration depth, $x(t)$, as a function of time, is derived by integrating Eq. (1)

$$x(t) = \frac{1}{\alpha} \ln(\alpha v_0 t + 1); \tag{2}$$

$$\alpha = \frac{C_d \rho_t S}{2 m_p} = \frac{3 C_d \rho_t}{4 d_p \rho_p} [m^{-1}], \tag{3}$$

where t, d_p, and ρ_p are the time from the impact and the projectile's diameter and bulk density, respectively. Using Eq. (2),

Table 1
Physical properties of porous targets investigated in the present and also previous studies and referred to in Figs. 3, 5, and 7.

Material	Type	Bulk density (g cm^{-3})	Compressive strength		Porosity, ϕ (%)
			Stronger part (MPa)	Weaker part (MPa)	
Sintered glass beads[a]	fluffy94	0.140 ± 0.004	0.47 ± 0.13	0.27 ± 0.04	94.4 ± 0.2
	fluffy87	0.340 ± 0.009	1.43 ± 0.040	0.86 ± 0.10	86.8 ± 0.3
	fluffy80	0.510 ± 0.020	–	–	80.3 ± 0.9
Sintered glass beads[b]	P35-R0	1.59	12.1 ± 3.4		36.5 ± 0.3
	P35-R12.5	1.69	15.3 ± 6.3		34.3 ± 1.0
	P35-R25	1.80	17.5 ± 5.9		32.3 ± 1.6
	P40-R0	1.49	1.91 ± 0.51		40.3 ± 1.8
Gypsum[c]	–	1.10 ± 0.05	15.6 ± 1.3[d]		50 ± 2
Foamed polystyrene[e]	*L*	0.011	0.07[f]		99.0[g]
	M	0.037	0.16[f]		96.5[g]
	H	0.074	> 0.2[f]		93.0[g]
Aerogel[h]	–	0.060	–		97.7[i]

[a] Detailed information about the sintered glass-bead targets fluffy80, fluffy87, and fluffy94 is given by Okamoto et al. (2013). The compressive strengths of targets with diameter/height ratios are determined based on the values of fluffy94 and fluffy87 with a diameter/height ratio of ~0.5. We adopted the strength of either the stronger or the weaker part in our analyses, depending on which of either the top or bottom surfaces was impacted by the projectile.
[b] Data of Hiraoka (2008), used in Figs. 5 and 7.
[c] Data of Yasui et al. (2012), used in Figs. 3 and 7.
[d] The compressive strength of gypsum with a porosity of 47 ± 3% from Fujii and Nakamura (2009) is adopted here.
[e] Data of Ishibashi et al. (1990), used in Figs. 5 and 7.
[f] Standard value (JIS A9511), corresponding to each bulk density.
[g] Porosity of the foamed polystyrene target is calculated assuming that the density of polystyrene is 1.056 g cm^{-3} (Chronological Scientific Tables, 2012).
[h] Data of Niimi et al. (2011), used in Fig. 3.
[i] Porosity of the aerogel target is calculated assuming that the density of silicon dioxide is 2.648 g cm^{-3} (Greenwood et al., 1984).

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