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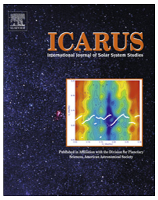

Impact strength of small icy bodies that experienced multiple collisions

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ABSTRACT

Frequent collisions are common for small bodies in the Solar System, and the cumulative damage to these bodies is thought to significantly affect their evolution. It is important to study the effects of multiple impacts such as the number of impacts on the impact strength and the ejection velocity of impact fragments. Here we conducted multiple-impact experiments using a polycrystalline water ice target, varying the number of impacts from 1 to 10 times. An ice cylindrical projectile was impacted at 84–502 m s^{-1} by using a single-stage gas gun in a cold room between -10 and -15 °C. The impact strength of the ice target that experienced a single impact and multiple impacts is expressed by the total energy density applied to the same target, ΣQ, and this value was observed to be 77.6 J kg^{-1}. The number of fine impact fragments at a fragment mass normalized by an initial target mass, $m/M_{t0} \sim 10^{-6}$, n_m, had a good correlation with the single energy density at each shot, Q_j, and the relationship was shown to be $n_m = 10^{1.02\pm0.22} \cdot Q_j^{1.31\pm0.12}$. We also estimated the cumulative damage of icy bodies as a total energy density accumulated by past impacts, according to the crater scaling laws proposed by Housen et al. (Housen, K.R., Schmidt, R.M., Holsapple, K.A. [1983]. J. Geophys. Res. 88, 2485–2499) of ice and the crater size distributions observed on Phoebe, a saturnian icy satellite. We found that the cumulative damage of Phoebe depended significantly on the impact speed of the impactor that formed the craters on Phoebe; and the cumulative damage was about one-third of the impact strength ΣQ^* at 500 m s^{-1} whereas it was almost zero at 3.2 km s^{-1}.

1. Introduction

In the evolution of Solar System bodies, collisional disruption has played an important role. For example, the proto-planets were formed by collisional disruption and the re-accumulation of planetesimals, and asteroids are believed to be survivors of planetesimals that experienced collisional disruption. In order to study the formation processes of Solar System bodies, the impact condition of catastrophic disruption for solid materials simulating various Solar System bodies should be clarified.

The impact condition for catastrophic disruption is called the impact strength, Q^*, and Q^* is one of the most important properties of Solar System bodies related to mutual impact. Q^* is defined by the energy density Q when the largest fragment mass is equal to one-half of the original target mass (Davis and Ryan, 1990), and the energy density Q is defined by the kinetic energy of the impactor (or projectile) divided by the original target mass. Over the past 30 years, many studies have been conducted to discern the impact strength of various solid materials simulating Solar System bodies, such as laboratory impact experiments using basalt and ice (e.g., Fujiwara et al., 1977; Kawakami et al., 1983; Takagi et al., 1984; Davis and Ryan, 1990; Kato et al., 1995).

As spacecraft explorations and ground-based observations have advanced, more and more details of Solar System bodies have been revealed. For example, some asteroids and small icy satellites have low bulk density, i.e., large porosity (Consolmagno and Britt, 1998; Britt et al., 2002; Porco et al., 2007), and they are composed of a mixture of several components such as ices and silicates. Intensive studies to elucidate the effects of the porosity and the mixture on the impact strength have been conducted using various porous materials and mixtures (e.g., Arakawa and Tomizuka, 2004; Shimaki and Arakawa, 2012). These studies clarified that the porosity and the multiple components significantly affected the impact strength, increasing or decreasing them. We propose that it is very important to study the impact strength of various materials simulating Solar System bodies with a wider range of physical and chemical properties.

One of the most important and most interesting physical properties is “multiple impacts”. The term “multiple impacts” refers to when a Solar System body has experienced many impacts with other bodies. In this study, we focused on Solar System bodies that have experienced multiple impacts. These bodies experienced

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multiple impacts are called as “pre-impacted bodies”. Laboratory experiments, exploratory observations, and numerical simulations have obtained some potential evidence of multiple impacts for small bodies such as asteroids, comets, and icy satellites. The many craters found on the small bodies are expected to be accompanied by many fractures under and around the craters, because laboratory impact cratering experiments in water ice and gypsum demonstrated that the impact craters were always surrounded by many cracks (Kato et al., 1995; Yasui et al., 2012). Veverka et al. (2000) found a large impact crater together with many grooves on the surface of Eros, and they suggested that the grooves may extend toward the interior as fractures. They speculated that the grooves might be formed simultaneously by the impact forming the crater. Michel et al. (2003) did numerical simulations of collisions of parent bodies to explore the properties of the Karin family (one of the large asteroid families), and the outcomes of the simulations showed that the Karin family members must be the products of collisions of a parent body that experienced impacts previously. In order to study the collisional evolutions of Solar System bodies, the impact strength of the bodies that experienced multiple impacts should be also clarified, because the pre-impacted bodies could have many fractures inside, so that their impact strength could be smaller than that of an intact body. It is thus important to know how the impact strength decreases with the number of impacts compared with the intact body.

Several experimental studies have investigated the effects of multiple impacts on the impact strength of small bodies by using target materials of glass and basalt simulating a tektite and an asteroid. Gault and Wedekind (1969) conducted impact experiments using spherical glass targets simulating a tektite at the impact velocity of 7.55 km s^{-1}, for 1, 4, 7, and 19 impacts on different impact surfaces. They examined the relationship between the largest fragment mass normalized by the original target mass, m_l/M_t, and the total energy density, ΣQ, where ΣQ was the sum of each projectile kinetic energy applied to the same target divided by the initial target mass. They found that the relationship was very similar to that obtained for single-impact experiments, irrespective of the number of impacts. Housen (2009) conducted impact experiments on cylindrical basalt targets at the impact velocity of 0.73–1.97 km s^{-1} and he studied a single impact and two impacts on the same and different impact surfaces. He reported almost the same result as that obtained by Gault and Wedekind (1969). Nakamura et al. (1994) also conducted impact experiments on a spherical basalt target at impact velocities of 2.8–3.2 km s^{-1} for a single impact and two impacts. We found that the result reported by Nakamura et al. was very different from that obtained by Housen (2009): the relationships between m_l/M_t and ΣQ in the two impacts was not consistent with that obtained by Housen (2009), whereas the relationship between m_l/M_t and the single energy density in the two impacts was almost similar to that obtained in single-impact experiments (Fujiwara and Tsukamoto, 1980; Takagi et al., 1984).

This difference could be caused by one or more target physical conditions such as the crack number density or distribution. Nakamura et al. (1994) used a barrel-shaped core fragment for the second shot, which was derived from an original target at the first shot. It was shown by a numerical simulation that the core fragment is not fractured so severely (Benz and Asphaug, 1993), and the pre-existing cracks inside the target given by the previous impacts in the target were fewer than that used by Housen (2009) in the second shot. Thus, in order to determine the precise effects of multiple impacts on the impact strength, the target physical conditions should be controlled. The crack number density and the distribution, in particular, should be systematically controlled.

In this study, we conducted multiple-impact experiments to study the effects of multiple impacts on the impact strength. We used a polycrystalline water ice target because there are no experimental results for multiple impacts using an ice target, and water ice is a transparent material that is suitable for recognizing cracks in the target. In order to control the crack number density and the distribution in the targets, we systematically selected the number of impacts, the energy density at each impact shot (the single energy density: Q_j), and the total energy density (ΣQ). We also measured the ejecta velocity and the size distribution of impact fragments to characterize the degree of the impact disruption. Lastly, we attempted to apply our laboratory results for the estimation of the internal damage of a saturnian icy satellite, Phoebe, by using the crater scaling law proposed by Housen et al. (1983) and the cumulative size distributions of impact craters observed on the satellite.

2. Experimental methods

2.1. Samples

We used polycrystalline water ice as a projectile and as a target simulating icy bodies such as icy satellites and comets. The projectile was cylindrical (15-mm dia., height of 9–11 mm), with the mass, m_p, of 1.40–1.66 g. It was made by putting tap water put into a mold, and then freezing the water in a cold room (−10 °C) for a few tens of minutes. The projectile looked cloudy because tiny bubbles were incorporated in it, and thus the projectile had a small amount of porosity (less than a few percent); however, the porosity did not affect the impact outcomes (Kato et al., 1995; Arakawa et al., 2002).

The target had a cubic shape with the initial mass ranging from 0.60 to 2.69 kg and the size from 8.7 to 14.0 cm. It was prepared by cutting a large commercial ice block. The density of the ice target was 917 kg m^{-3}, and the target was so-called “columnar ice” with large ice crystals elongated toward one direction with the size of several cm (Kato et al., 1995). There were no bubbles in it, so it looked completely transparent.

2.2. Impact experiments

We conducted impact experiments by using a one-stage light-gas gun installed in a cold room at the Institute of Low Temperature Science, Hokkaido University. A schematic illustration of the experimental setup is shown in Fig. 1. The impact velocity, V_i, ranged from 84 to 502 m s^{-1}. The room temperature was set between −10 and −15 °C.

In the present study, an ice projectile was impacted on the same target from 1 to 10 times (=the number of impacts), and each impact was conducted on different target surfaces: the projectile was impacted on the intact surface up to four times, after that the surface that experienced the impact before was impacted again. A second shot was given to the opposing surface of the first shot, a third shot was given to the surface perpendicular to those of the first and second shots, and a fourth shot was given to the opposing surface of the third shot, and so on. We used these four surfaces to give the impact on the target, and then these surfaces were impacted two to three times repeatedly in one series of experiment for fifth to tenth shots. The other two intact surfaces were used for a window to observe the generated cracks inside the target.

In the present study, we describe the target mass according to the number of impacts: (1) the target mass before the first impact, M_{t0} (initial target mass), and (2) the target mass before the jth impact ($j = 2$–10), M_{t_j}. We describe the impact condition by using two parameters: (1) the energy density at each shot or a single energy density, Q_j, where the subscript j is the number of impacts, and (2) the total energy density, ΣQ, which corresponds to the sum of each energy density applied to the same target, that is,