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High- and low-velocity impact experiments on porous sintered glass bead targets of different compressive strengths: Outcome sensitivity and scaling

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ABSTRACT

Impact experiments on porous targets consisting of sintered glass beads have been performed at different impact velocities in order to investigate the disruption impact energy threshold (also called Q^*) of these targets, the influence of the target compressive strength on this threshold and a scaling parameter of the degree of fragmentation that takes into account material strength. A large fraction of small bodies of our Solar System are expected to be composed of highly-porous material. Depending on their location and on the period considered during the Solar System history, these bodies collide with each other at velocities which cover a wide range of values from a few m/s to several km/s. Determining the impact response of porous bodies in both high- and low-velocity regimes is thus crucial to understand their collisional evolution over the entire Solar System history, from the early stages of planetary formation through collisional accretion at low impact velocities to the current and future stages during which impact velocities are much higher and lead to their disruption. While these problems at large scale can only be addressed directly by numerical simulations, small scale impact experiments are a necessary step which allows the understanding of the physical process itself and the determination of the small scale behavior of the material used as target. Moreover, they are crucial to validate numerical codes that can then be applied to larger scales.

Sintered glass beads targets of different shapes and porosity have been built and their main material properties, in particular their compressive strength and their porosity, have been measured. The outcomes of their disruptions both at low and high impact velocities have then been analyzed.

We then found that the value of Q^* strongly depends on the target compressive strength. Measuring the particle velocities as a function of their distance to the impact point, we first found that the attenuation rate of the stress wave in our sintered glass bead targets does not depend on the impact velocity regime. Ejecta velocities as a function of the distance from the impact point can thus be well fitted by a power law with an exponent about -2 in both velocity regimes. We then looked for a scaling parameter that can apply to both regimes. We found that the scaling parameter *PI*, which is related to the initial peak pressure and to the stress wave attenuation can be used to represent the outcome in a general way. Future investigations will be performed to determine whether these results can be generalized to other kinds of porous materials.

1. Introduction

In this paper, we present our experiments on porous targets consisting of sintered glass beads, including their making and the outcome of their disruption at low and high impact velocities.

The populations of asteroids and comets are characterized by a great diversity in compositions and structures. A large fraction of these populations is thought to consist of porous bodies with low bulk density, such as the main belt Asteroid (253) Mathilde which was observed by the NEAR spacecraft in 1997 (see e.g. Yeomans et al., 1997) and whose measured bulk density is 1.3 g/cm^3. In order to understand the collisional history and evolution of small bodies, it is therefore important to have a good knowledge of their impact response as a function of their physical properties. This is

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also required in the framework of mitigation strategies aimed at deflecting a potentially dangerous object. In recent years, it has been realized that the impact response of porous objects is likely to be very different than the one of non-porous bodies. In particular, both the impact energy required to achieve a given degree of disruption and the outcome properties may highly depend on the object's porosity.

Housen et al. (1999) found that impacts on porous bodies in the cratering regime can lead to crater formation by compaction, which means that basically no material is ejected, while excavation is observed on solid targets. Moreover, porous bodies may be more resistant to impacts because of their decreased ability to transmit stress waves. This argument was proposed as a possible explanation of the presence of huge craters on Mathilde which were a priori not expected. Indeed, the impact energy required to form them should have disrupted the body if it behaved as a purely solid non-porous one. Moreover the craters' morphology was closer to the one expected from compaction, although it remains unclear whether excavation cannot lead to the same outcome.

The physics of the fragmentation is still a subject of intensive research, and our understanding is still poor. This is even truer when a porous material is considered. Therefore, impact experiments on porous targets are crucial to improve our understanding at small scale, and to determine the important physical processes and parameters that are involved. Moreover, they are the only data that can be used to validate numerical codes before those are applied at larger scales adapted to planetary science (e.g. asteroid disruptions). Recently, numerical codes of fragmentation, called hydrocodes, have been improved to include a model of fragmentation suitable for porous materials (see e.g. Jutzi et al., 2008). The validation of numerical codes relies on their ability to reproduce impact experiments by using the same material parameters and impact conditions as those used in the experiments. Such a validation process has already started using pumice as a porous material (Jutzi et al., 2009). However, the variety of porous materials and their respective response to impacts are so wide that a good general knowledge of the impact process on such objects can only be achieved by constructing a database of impact experiments on targets covering a wide range of material properties.

Laboratory studies of the impact process on porous small bodies have provided valuable data about the relation between impact strength and porosity. Arakawa et al. (2002) and Arakawa and Tomizuka (2004) conducted impact experiments on pure ice and ice–silicate mixture targets with porosity up to 55%. Their results showed that the impact strength of pure ice increased with increased target porosity, but the impact strength of mixture target had an opposite tendency, i.e. the impact strength decreased with the increase of porosity. Impact experiments using porous ice and snowball targets with porosity of 30–45% (Ryan et al., 1999) and 39–54% (Giblin et al., 2004) were conducted to simulate Kuiper-Belt Objects in structure. Ice chips with different mass distributions were bounded together by partial melting and refreezing to form porous ice targets. Ryan et al. (1999) found that the impact strength of porous ice targets was higher by a factor of about 5 than that of solid ice targets. Then, Giblin et al. (2004) found that the impact strength of targets consisting of ice fragments was higher than that of snowballs.

In order to improve our knowledge of the impact response of porous targets and to provide some benchmarks to numerical simulations, we have undertaken a campaign of impact experiments on porous targets. As a first step, we manufactured targets made by sintering of glass beads. Love et al. (1993, hereafter L93) and Michikami et al. (2007) have already performed a few experiments using sintered glass beads. L93 showed that porosity has a major influence on the required impact energy to achieve a fixed degree of disruption. The specific impact energy is usually called Q and is defined as the kinetic energy of the projectile normalized by the target's mass. The disruption impact energy threshold Q^* corresponds to the impact energy leading to a largest remnant having half the mass of the target. In this paper, we investigate the dependency of Q^* on the compressive strength. We performed experiments both at high and low impact velocities. As we will see, the value of Q^* is highly sensitive to the compressive strength. Then, we looked for a scaling parameter that takes material strength into account. Our results suggest that the scaling parameter *PI* (see Section 5.2) proposed by Mizutani et al. (1990), which is related to the initial peak pressure and to the stress wave attenuation, is an appropriate scaling parameter of our experiments.

The making of our sintered glass bead targets and their properties are presented in Section 2. Impact experiments at low velocities are described in Section 3, while those at high velocities are exposed in Section 4. Section 5 presents our investigations of the stress wave attenuation rate in our targets, and then of the scaling parameter *PI*. Conclusions are finally exposed in Section 6.

2. Characteristics of the targets and manufacture method

Different kinds of targets have been manufactured for our experiments. They were all produced by sintering soda lime glass beads of 50 μm diameter and 2.5 g/cm^3 nominal density. Bulk porosity of soda lime glass beads is 40%, which is close to the minimum porosity expected for dark porous asteroids (Britt and Consolmagno, 2000). The gap size is similar to or smaller than the constituent particle size, therefore the porosity is considered as "microporosity" (Britt et al., 2002). Sintered glass beads can achieve various compressive strengths while maintaining the same degree of porosity. Additionally, they have brittle properties like rocks. These glass beads were poured into a mold and the mold was positioned at the center of an oven and baked. We defined four groups of targets differing from each other by the manufacturing process, as described in the following. The targets of Groups 1, 2 and 4 will be used in our experiments at low impact velocities, while targets of Groups 3 and 4 will be used in our experiments at high impact velocities (see Sections 3 and 4). Table 1 summarizes their properties.

2.1. Targets of Group 1: tea cups

Targets of Groups 1-A and 1-B consist of 50-g mass tea-cup shape targets with similar porosities (~40%) but different compressive strengths. They correspond to a sub-set of targets that have already been used by Setoh et al. (2007a) to investigate the effect of the compressive strength on the impact outcome, keeping the porosity constant. The glass beads were heated in an alumina mold with different baking conditions. The tea-cup shape mold was 4 cm in top diameter, 3 cm in bottom diameter and 3 cm deep.

Group 1-A targets were produced at the same maximum temperature but varying the baking duration at this temperature level. Thus, they were heated from room temperature to 650 °C over 25 min, and the temperature was kept at this level for 10, 20 and 30 min, respectively, at which point the heater was switched off.

Group 1-B targets were produced at different maximum temperatures, but keeping the same baking duration at the maximum temperature level. Thus, they were produced by heating them from room temperature to 630, 640, and 660 °C, respectively, and the same baking duration of 30 min at the maximum temperature level. The error of baking temperature was within 2 °C. Therefore, the targets heated for 30 min at 650 °C are present both in Groups 1-A and 1-B.

The compressive strengths of Groups 1-A and 1-B targets have been measured by an uniaxial compressive testing machine in