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The shapes of fragments from catastrophic disruption events: Effects of target shape and impact speed

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ABSTRACT

We conducted impact experiments at the NASA Ames Vertical Gun Range in the context of an ongoing set of experiments to investigate both target shape and impact speed effects on fragment shapes and mass–frequency distributions in collisions on basalt targets. In this work we present the first part of that set, regarding mostly target shape effects. We impacted both irregularly-shaped and spherical basalt targets at speeds ranging from ~4–6 km/s. We obtained mass–frequency distributions from fragments recovered from the impact chamber and measured fragments shapes using a combination of image analysis and manual measurements with a caliper. We find that the characteristics of the mass–frequency distributions and the range of fragment shapes show no significant dependence on target shape (i.e., flat, 'shell-like' fragments are produced in impacts into irregularly-shaped targets as well as spherical ones). We note that many thin, plate-like impact fragments seem to originate from lower-speed impacts and can originate from the interior of the targets (in addition to the flattened fragments often seen to origin from the near-surface spall zone in cratering impacts). We measure the porosity of aggregates made by artificially (but randomly) reassembling fragments from each impact to be on the order of 50%, significantly larger than that for hexagonal lattice and random packing of equal sized spheres.

1. Introduction

Recent experiments showing 'onion shells' of tabular-shaped fragments from impacts into spherical targets (Walker et al., 2013; Nakamura, 2014 personal communication) have re-opened the question of the fracture mechanics responsible for determining fragment shape in catastrophic impacts. Fujiwara et al. (1978) presented the first work on the topic of shapes of fragments from impact experiments in the context of asteroid studies. Fujiwara et al. (1989) suggest two modes of catastrophic disruption for targets in laboratory impact experiments: (1) 'core-type' fragmentation in the high-speed, high-energy-density regime; and (2) 'cone-type' fragmentation in the low-speed, low-energy-density regime. These effects appear to be scale invariant, at least over the range of cm to m-scale target sizes investigated in laboratory impact experiments conducted to date. Fig. 1a, for example, shows the result of one of the cratering impacts into 1-m-diameter granite spheres reported in Walker et al. (2013). In these experiments aluminum spheres of 4.45-cm diameter were impacted into the granite targets at speeds of 2 km/s. Many of the larger fragments recovered from the experiment enclosure exhibited thin, tabular shapes and the fractured walls of the resulting spall craters displayed the same plate-like nature of the many fragments 'peeled off' the outer shell of the granite 'onion'. Very similar fragment morphology is seen at smaller scales as well—Fig. 1b shows the largest remnant of an impact into a 5-cm-diameter soda lime glass sphere at 2 km/s, exhibiting the same flattened, tabular-shaped fragmentation pattern in the near-surface spall zone (Nakamura, 2014 personal communication). Similar behavior is seen in impacts into ~6–10-cm-diameter basalt spheres, as reported by Fujiwara and Tsukamoto (1980; Fig. 5) who present sketches of cross-sectional views of reconstructed targets showing shell-like fracture surrounding the remnant cores.

Because of the propensity of many previous laboratory investigations to focus on idealized spherical targets there exists some ambiguity in decoupling the relative importance/influence of impact speed versus spherical shape in producing the 'onion shell' fragment shapes seen in these experiments. If plate-like fragment shapes are due primarily to impact speed/energy density as

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suggested by Fujiwara et al. (1989) this could play an important role in the outcome of impacts onto small monolithic objects in the main asteroid belt due to the non-negligible probability of low-speed (i.e., below about 3–4 km/s—subsonic in rock) impacts there (Bottke et al., 1994). There is growing interest in spall-type impacts into initially monolithic rock targets due to the focus on smaller near-Earth asteroids (NEAs) – and the blocky fragments in coarse regoliths observed to exist on objects like Itokawa (Nakamura et al., 2008; Noguchi et al., 2010) – as targets for exploration missions and mitigation activities (Holsapple and

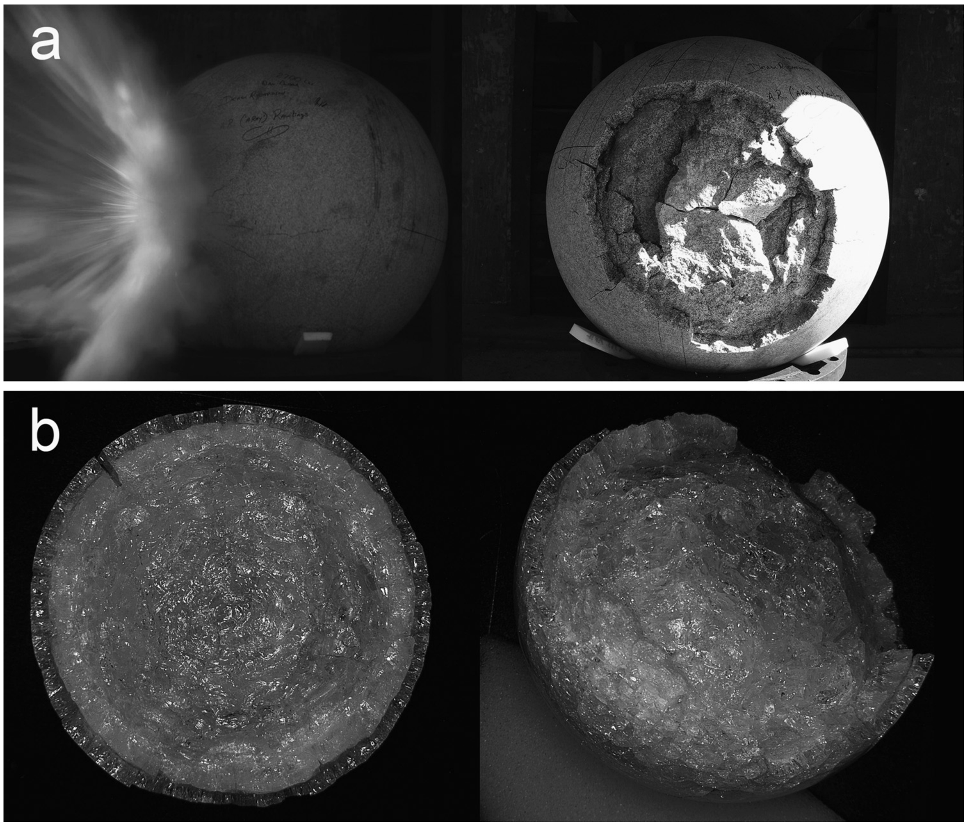

Fig. 1. (a) Cratering experiments on 1-m-diameter granite spheres (Walker et al., 2013) showing a trend toward flat, plate-like shapes for fragments spalled from the near surface regions surrounding the crater. The impact speed was 2 km/s. (b) Disruptive impacts into 5-cm-diameter soda-lime glass spheres at the same speed display a very similar fragmentation pattern (Nakamura, 2014 personal communication).

Fig. 2. Our typical irregularly-shaped and spherical basalt targets. The natural, irregularly-shaped targets are hand specimens collected in the field from the sample site. The spherical targets we prepared from larger fragments of the same basalt; the darker color is due to infusion of lubricating oil used during the milling process to obtain the spherical shape. The targets shown here were not shot during this experiment run; they remain for future impact experiments.