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Dynamic fragmentation of planetary materials: Sub-hypervelocity ejecta measurements and velocity scaling

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ABSTRACT

Ejecta velocity measurements were made during impacts into solid planetary materials. Ejecta velocity fields overlie each other when normalized by v_{max}, $v_{50\%\ mass}$, and $v_{50\%\ KE}$; these correspond to the maximum velocity and median values of mass and kinetic energy among ejecta velocities. Semi-empirical models were developed to provide predictive capabilities of 10th, 50th, and 90th percentiles of the distributions of mass, momentum and kinetic energy with respect to ejecta velocity. Lastly, a functional equation describing the probability density distribution of mass, momentum and kinetic energy among ejecta velocities was derived. Data and predictive models are valuable in the development and validation of numerical models, where comparison between experiments and simulations rely on well characterized measurements.

1. Introduction

This paper examines experimental measurements of ejecta velocity during impacts into finite solid targets of geological materials. Experimental measurements of ejecta velocity have been previously investigated by many authors (Gault and Heitowit, 1963; Stöffler et al., 1975; Piekutowski et al., 1977; Hartmann, 1985; Yamamoto and Nakamura, 1997; Cintala et al., 1999; Yamamoto et al., 2005; Schultz, 2006; Michikami et al., 2007; Shuvalov and Trubetskaya, 2008; Jutzi et al., 2010; Housen and Holsapple, 2011; Hermalyn et al., 2012). A compilation of past experiments can be found in the recent review of Housen and Holsapple (2011). Past studies primarily deployed vertical impacts to simulate impact cratering processes into granular (Hermalyn and Schultz, 2010) and analog lunar and asteroid materials (Hartmann, 1985). Ejecta velocity measurement data have also been obtained in numerical simulations (Jutzi et al., 2010). However, despite vast improvements, challenges still remain when reproducing ejecta cloud formation and deposit characteristics in numerical simulations (Artemieva et al., 2009). For this reason, additional, well characterized, experiments of ejecta velocities are needed and such measurements are investigated in this study.

There have been numerous methods used to measure ejecta velocity. Piekutowski et al. (1977) and Cintala et al. (1999) determined ejecta trajectories using a laser sheet to illuminate fragments captured by a high-speed camera. Once fragments were identified, ballistic equations were used to back calculate velocities. Vector fields of discernible ejecta have also been traced onto photographs (Fujiwara and Tsukamoto, 1980), but restricted interrogation area and image resolution, coupled with triggering issues, reduce the total number of fragments that can be measured using these methods. More recently, particle image velocimetery (Anderson et al., 2003) and particle tracking velocimetry (Hermalyn and Schultz, 2010) have been used to track ejecta fields. Such experiments are difficult to perform and the total number of fragments recorded is limited due to the cluttered nature of the debris field at impact speeds > 1 km/s. This renders achieving a complete data set challenging.

In order to resolve some of the previous challenges with ejecta tracking, this study investigates ejecta velocity measurements for sub-sonic[1] impact conditions. Solid, finite geological targets are selected and the projectile diameter is comparable to the target thickness. Applications to planetary science for this configuration include areas where low velocity studies are important, such as secondary ejecta from large impacts and impacts from bodies

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[1] The sound speed is referenced to the target material.

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moving with a low (sub 1 km/sec) relative velocity, such as bodies in the asteroid belt. In all cases, understanding fragmentation and material ejection at these velocities may enable better interpretations at higher collision speeds (Schultz, 2006; Shuvalov and Trubetskaya, 2008; Housen and Holsapple, 2011; Hermalyn et al., 2012).

This investigation is a part of a broader study by Hogan et al. (2011, 2012, 2013a,b) on the dynamic fragmentation of planetary materials during impact. Two important stages of impact events are quantified: (1) fragmentation and (2) material ejection. To date, this work has been primarily focused on quantifying fragmentation (Hogan et al., 2012, 2013b) and investigating micro-scale thermal and fracture effects (Hogan et al., 2011, 2012, 2013b). Fragmentation results have been shown to have good agreement with theoretical models of fragment sizes (Zhou et al., 2006; Grady, 2009). Particle tracking methods used here were also implemented in Hogan et al. (2013a) to quantify ejecta velocity, size, mass, momentum and kinetic energy distributions during dynamic fragmentation of gabbro. Image enhancement and post-processing improvements have been made to the tracking algorithm, and tests have been performed for an additional three types of granitoid. The results of a total of 76 experiments for six target thicknesses (7–55 mm) and impact velocities of 20–550 m/s are compiled here. Ejecta field shapes and the distribution of the mass, momentum, and kinetic energy among ejecta velocities are examined. Non-dimensional scaling laws are developed from the extensive set of experimental results and implications discussed. Well characterized experimental data and methodologies for understanding the subsonic fragmentation of planetary materials is provided.

2. Experimental setup and analysis methods

The impact tests were performed at the French-German Research Institute of Saint-Louis (ISL), France. Target materials, target thicknesses, and impact velocities and energies are displayed in Table 1. Target materials, target configuration and projectiles are shown in Fig. 1. The order of materials based on the increasing SiO_2 content is gabbro (Fig. 1b), coarser grained monzonitic granitoid (monzonite) (Fig. 1d), finer grained syenite granitoid (syenite) (Fig. 1c), and finer grained tonalitic granitoid (tonalite) (Fig. 1a with target holder). Glass-fibre reinforced composite projectiles (45 g) (as displayed on the right in Fig. 1e) were used for the fine grained syenite blocks, whereas aluminum projectiles (65 g) (as displayed on the left in Fig. 1e) were used for the others. The finer-grained block experiments with the composite projectile were performed before aluminum projectiles were developed. The effect of projectile composition is not considered in this paper, but it is worth noting that projectile density and strength will have an effect on the early-time energy coupling of the impact. Composite projectiles can explode upon impact, thereby coupling less kinetic energy to the target. The flat projectile face configuration yields flyer-plate like conditions at impact, where the propagated shock-wave induces fragmentation and ejection of the material. Fragmentation through crushing also occurs at the projectile–target interface. Targets were sandwiched in fitted windowed metal plates and were allowed to expand laterally (Fig. 1a) .

3. Particle tracking methods

A Photron APX Ultima video camera filming at a 8 kHz frame rate captured images of material ejected from the rear of the targets. Two high-powered lamps were used to back-illuminate the particles against a black background (Fig. 2). Proper lighting and contrast between fragments and background is critical for image enhancement. A tracking algorithm written in Matlab (2013) was implemented to track ejecta larger than 1 mm (equivalent to three camera image pixels) over multiple high-speed camera images. Here it is assumed that a two-dimensional projection of the field onto the image is suitable for reliable results.

Pre-processing involves background subtraction and image enhancement within an interrogation window to make the ejecta more distinguishable (Fig. 2b). The size of the window is determined by the expansion of the debris cloud, where a greater expansion results in a larger initial window size. This is done in order to maximize the highest number of possible fragments to be tracked during the early stages of the debris field formation. Shown in Fig. 2a and b are examples of video and enhanced images for tonalite at 20 m/s and a target thickness of 10 mm. In this case, and in many low-speed cases, there are relatively few, but easily distinguishable fragments.

For more cluttered debris fields, image enhancement is performed in two stages. The first stage involves identifying and enhancing fragments >3 mm, as was done for less cluttered fields. Connected larger fragments are isolated, identified fragments are removed, and the second stage is applied. The second stage involves discretizing the remaining window and performing sub-enhancement of cluttered regions. Fragments are identified as brighter areas in these sub-regions. An example of an enhanced highly cluttered debris field is shown in Fig. 2d and e.

Once the images are enhanced, fragment size, shape, and position are determined using two consecutive frames, and a probable match algorithm is used to identify these fragments in both frames. The displacement of the particle over time yields velocity. In order or improve algorithm computation times, fragments were assumed to travel in the positive x-direction and remain ordered in space and time.

Post-processing of the velocity fields involves smoothing erroneous vectors by using a weighted spatial average of larger, well-determined, fragment velocities. Examples of velocity vectors are shown in Fig. 2c. θ is defined as $\arctan(vy/vx)$ and is referred to here as the ejection angle. The ejecta angles are taken as the

Table 1
Material type, number of experiments, target thicknesses, and impact velocities and energies.

Material type	Number of experiments	Target thickness (mm)	Impact velocities (m/s)	Impact energies (J)
Gabbro	19	10	26–100	21–305
Tonalitic granitoid	6	7	46–92	66–262
Tonalitic granitoid	11	10 (series 1)	20–95	12–280
Tonalitic granitoid	7	10 (series 2)	152–240	716–1786
Tonalitic granitoid	11	20	35–202	38–1265
Tonalitic granitoid	7	30	96–284	286–2500
Tonalitic granitoid	6	40	171–269	906–2243
Syenitic granitoid	5	55	347–550	2709–6806
Monzonitic granitoid	4	55	250–313	1938–3037