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Dynamic fragmentation of planetary materials: Ejecta length quantification and semi-analytical modelling

James D. Hogan [a,*], John G. Spray [c], Robert J. Rogers [b], Gregory Vincent [d], Markus Schneider [d]

[a] Hopkins Extreme Materials Institute, The Johns Hopkins University, Baltimore, MD 21218, USA
[b] Department of Mechanical Engineering, University of New Brunswick, Fredericton, New Brunswick E3B 5A3, Canada
[c] Planetary and Space Science Centre, University of New Brunswick, Fredericton, New Brunswick E3B 5A3, Canada
[d] ISL, 5 rue du Général Cassagnou, 68300 Saint-Louis, France

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ABSTRACT

The dynamic fragmentation of planetary materials during impact into finite targets has been examined. A particle tracking algorithm was implemented to estimate the size and velocity of fragments ejected from the rear of the target. A total of 76 experiments were performed for four materials, target thicknesses of 7 mm–55 mm, and impact energies of 10 J–6810 J. Semi-empirical models were developed from non-dimensional groups to predict key experimental results. This includes the transformation of incoming projectile kinetic energy to the ejecta kinetic energy. The amount of impact energy converted to kinetic energy of ejecta was found to increase from 2% to 18% over the range of test conditions. Energy dissipated into expanding the field laterally was found to be small in comparison to the streamwise direction ($\sum KE_y / \sum KE_x = 4\%$).

Percentiles of the distribution of mass, momentum and kinetic energy with respect to ejecta lengths were also examined. Percentile ejecta lengths decrease for increasing normalized impact energy. Fits of the non-dimensional ejecta lengths provide reasonable collapse for the percentile values. Lastly, the cumulative distributions of mass, momentum and kinetic energy among normalized 50% length values were quantified. Exponential function forms were found to fit all of the data over the range over normalized length scales of 0.3–4. When integrated, this predicts the probability density distribution of mass, momentum, and kinetic energy among ejecta lengths for the range of experimental conditions in this study. This data is important in the development and validation of numerical models.

1. Introduction

The complex dynamic response of planetary materials (e.g., rocks) subject to impact arises from the interactions of material properties and resulting fracture behaviours under multi-axial stress states. During dynamic fragmentation, fracture initiates at pre-existing flaws and propagates in response to local tensile stresses acting perpendicular to the fracture plane [1]. This failure propagates at the bulk scale down to the micro-scale, resulting in a cascade of associated plastic and thermal effects [2]. Understanding the dynamic fragmentation of planetary materials is important in seismology and earthquake science [3], volcanology [4], and in planetary and space science [5–8] (e.g., Deep Impact ejecta [9], LCROSS [10]).

Planetary materials are commonly brittle and the strain rate of loading is influential during their dynamic fragmentation. At low to moderate strain rates (250 s^{-1} to 25,000 s^{-1}), the distribution of defects controls fragmentation [11]. At higher strain rates (approximately $>$ 25,000 s^{-1}), fragmentation is mainly a kinetic process and the influence of internal defects is less [12]. A direct result of fragmentation at high strain rates is that the failure strength increases and becomes less stochastic [13,14]. In addition, at high strain rates, the initial fragmentation process represents a fraction of the final number of fragments generated during loading [15]. The majority of fragmentation (in terms of number generation) occurs through the interaction of fractured surfaces [16].

The partitioning of impact energy into fragmentation (or fracture) energy, kinetic energy, heat, acoustic emissions, and elastic strain energy remains difficult to assess. Efficiencies[1] of ∼1% to

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* Corresponding author.
E-mail address: jd.hogan@jhu.edu (J.D. Hogan).

[1] Defined as the ratio of fracture surface area energy generated to mechanical strain energy input [17].

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~2% [18–20] have been reported for fragmentation energy. Similar conversion rates have been reported during impact tests [21,22]. Higher efficiencies (~15%) are estimated when the ratio of energy required for single particle fracture to mechanical input energy is considered instead of the ratio of the energy of creating new surface area to mechanical energy [17]. Acoustic emissions account for approximately 3% of energy during fracture [23]. Upwards of ~26% of impact energy can be transformed to heat generated via friction in high speed (>6 km/s) impact experiments into granular media [24]. Thermal dissipation likely accounts for more than this as it is believed to represent 99% of the amount of energy that is dissipated into fracture (with 1% going into making the new surface) [25,26]. In impact tests into solid planetary materials, a significant amount of heat is generated via shearing of adjacent fracture surfaces [22]. It is difficult to assess the total conversion of impact energy to heat, but is believed to be the greatest source of energy dissipation.

In a detailed study on energy partitioning in rock blasting, Sanchidrian et al. [27] noted that 2%–6% of the total energy is converted to fragmentation energy, 1%–3% to seismic energy (i.e., elastic energy) and 3%–21% for kinetic energy. The remaining 70%–94% is likely dissipated into heat. Energy partitioning during hypervelocity impact was investigated, primarily using a 1-dimensional wave calculation code, in an early study by Gault and Heitowit [28]. They noted that <1% is converted to elastic wave, 19%–23% of impact energy is converted to waste heat, 10%–24% converted to comminution (i.e., fragmentation), and 43%–53% was converted to ejecta translational kinetic energy. The conversion of impact energy to translational kinetic energy is investigated in this paper and its distribution among ejecta sizes is considered.

There have been numerous analytical models predicting average ejecta (i.e., fragment) size during the dynamic fragmentation of brittle materials. In one class of theories, geometric statistical considerations are used to predict the distribution of fragment sizes [29,30]. Grady [31] derived an analytical model for an average fragment size based on an energy balance between the surface energy released due to fracture and the kinetic energy of the fragments. Glenn and Chudnovsky [32] refined the Grady model to account for the strain energy of the fragments. The major limitations of energy models arise from accurately determining how much of the total energy is dissipated into the generation of new surfaces. Models have also been proposed based on numerical simulations, which involve cohesive finite element schemes [33] that can account for, as an example, material flaw distribution [34,35]. Zhou et al. [36] have successfully implemented these schemes and developed fragment prediction models for three-dimensional fragmentation scenarios. These models are explored further in the paper.

This paper examines ejecta lengths during the dynamic fragmentation of planetary materials. It is a part of a broader study by Hogan et al. [2,16,22,37] to characterize the high rate behaviour of geological materials during impact. Two important stages of impacts are quantified: (1) fragmentation and (2) material ejection. To date, this work has been primarily focused on characterizing micro-scale failure processes (e.g., thermal and fracture effects [2,16,22]) and quantifying fragmentation distributions using particle sizing technologies and methods [2,16]. Fragmentation results have been shown to have good agreement with theoretical models of fragment sizes (e.g., Grady [31], Zhou et al. [36]). In a more recent paper (Hogan et al. [37]), ejecta velocity, size, mass, momentum and kinetic energy distributions during dynamic fragmentation of gabbro were examined. Ejecta measurements were made using a developed particle tracking algorithm. Since this work, image enhancement and post-processing improvements have been made to the tracking algorithm. The distributions of mass, momentum, and kinetic energy with respect to ejecta lengths are investigated for 76 data sets in this paper. Fragmentation distributions are compared with theoretical prediction of average fragment sizes.

Semi-empirical non-dimensional scaling relationships are developed to collapse results for the 76 data sets. The development of fitted non-dimensional groups allows results to be viewed in a broader context by incorporating varying and important experimental conditions (e.g., target thickness, material type, and impact energy). These models can be extrapolated to predict the distribution of mass, momentum and kinetic energy among length scales for other brittle materials across a range of impact energies. It also provides reference for those numerically simulating these complex multi-scale events.

2. Experimental setup and analysis methods

The impact tests were performed at the French-German Research Institute of Saint-Louis (ISL), France, using an electromagnetic railgun. Materials, target thickness, and impact velocities and energies are given in Table 1. Impact velocities were measured using Doppler radar and are assumed accurate to plus or minus 3 m/s. Impacts occurred at the centre of the target (confirmed from post-impact analysis of damaged targets). Materials include a finer grained tonalitic granitoid, gabbro, a finer grained syenitic granitoid, and a coarse grained monzonitic granitoid. Photographs of the target materials, target holder, and projectiles are shown in Fig. 1. The targets were sandwiched in the steel target holder. The targets were primarily constrained in the incoming shot direction, and were allowed to expand laterally. Projectiles were hexagonal in shape and 30 mm in length. The geometry of the projectile in the hexagonal-shaped bore of the railgun and the proximity of the barrel exit with respect to the target (1 m from the barrel exit) prevented yaw and pitch effects at impact. Composite projectiles (45 g) were used for the syenitic granitoid and aluminium projectiles (65 g) were used for the tonalite, monzonite and gabbro materials. No visible spalling occurred in the aluminium projectile and minor deformation is noted.

2.1. Particle tracking algorithm

A tracking algorithm written in Matlab [38] is implemented to track ejecta larger than 1 mm (determined as 3 pixels by the resolution of the camera) over multiple Photron APX Ultima high-speed camera images. The capture rate was 8 kHz. Ejecta were made distinguishable through background subtraction and image enhancements. Shown in Fig. 2 is an example of a high-speed image for tonalite at 20 m/s and a target thickness of 10 mm. The first set of measurements are taken when the debris cloud has the greatest expansion in the field of the view of the camera so as to record the most possible fragments. This is indicated by the yellow rectangle

Table 1
Material type, number of experiments, and impact velocity and kinetic energy.

Material type	Number of experiments	Target thickness (mm)	Impact velocities (m/s)	Impact energies (J)
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
Gabbro	19	10	26–100	21–305
Syenitic granitoid	5	55	347–550	2709–6806
Coarse monzonitic granitoid	4	55	250–313	1938–3037