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Scale-dependent measurements of meteorite strength: Implications for asteroid fragmentation

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ABSTRACT

Measuring the strengths of asteroidal materials is important for developing mitigation strategies for potential Earth impactors and for understanding properties of in situ materials on asteroids during human and robotic exploration. Studies of asteroid disruption and fragmentation have typically used the strengths determined from terrestrial analog materials, although questions have been raised regarding the suitability of these materials. The few published measurements of meteorite strength are typically significantly greater than those estimated from the stratospheric breakup of meter-sized meteoroids. Given the paucity of relevant strength data, the scale-varying strength properties of meteoritic and asteroidal materials are poorly constrained. Based on our uniaxial failure studies of centimeter-sized cubes of a carbonaceous and ordinary chondrite, we develop the first Weibull failure distribution analysis of meteorites. This Weibull distribution projected to meter scales, overlaps the strengths determined from asteroidal airbursts and can be used to predict properties of to the 100 m scale. In addition, our analysis shows that meter-scale boulders on asteroids are significantly weaker than small pieces of meteorites, while large meteorites surviving on Earth are selected by attrition. Further, the common use of terrestrial analog materials to predict scale-dependent strength properties significantly overestimates the strength of meter-sized asteroidal materials and therefore is unlikely well suited for the modeling of asteroid disruption and fragmentation. Given the strength scale-dependence determined for carbonaceous and ordinary chondrite meteorites, our results suggest that boulders of similar composition on asteroids will have compressive strengths significantly less than typical terrestrial rocks.

1. Introduction

Modeling studies of asteroid disruption and fragmentation (Melosh et al., 1992; Benz and Asphaug, 1999) use strength and fracture properties derived from experiments using analog materials such as basalt, granite, or lunar rocks (Durda et al., 2011), even though these are unlikely to be representative of asteroid materials (Flynn and Durda, 2004). Knowledge of in situ strength behavior, at a variety of scales and rates, is important to sample return missions (Berry et al., 2013; Brophy and Murhead, 2013) resource utilization, robotic manipulation, and hazardous asteroid mitigation. Observational and experimental evidence (Melosh et al. 1992; Housen and Holsapple, 1999; Consolmagno and Britt, 1998; Fujiwara et al., 2006) suggests that most ∼300-m- to ∼30-km-sized asteroids are rubble piles. For example, 25,143 Itokawa, the ∼300 m target of the Hayabusa sample return mission (Fujiwara et al., 2006), is dominated by regolith of micron-sized dust to 30-m-sized blocks, with particle diameter following a D^{-3} power law size distribution (Barnouin-Jha et al., 2008), possibly throughout the interior, indicating an ongoing disruption process on small asteroids. But to date there is little understanding of the strength properties in this environment, and whether meteorites found on Earth are characteristic of asteroidal materials. Here we show how material properties extrapolate from cm-scales (of laboratory samples and small gravels on asteroids) to meter-sized objects, the

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latter including the multi-meter meteoroids that impact Earth's atmosphere (Popova et al., 2011; Borovička et al. 2015).

There have been relatively few studies of the physical properties of meteorites. Most measurements have been non-destructive such as bulk density, thermal conductivity, and elastic constants (Consolmagno et al., 2008; Ibrahim, 2012). Few measurements of meteorite strength have been undertaken, as the samples have to be crushed. As such catastrophic disruption modeling (Melosh et al., 1992, Benz and Asphaug, 1999) parameters have so far been obtained from studies of terrestrial analogs (e.g., basalt and concrete) or from studies limited to single specimens of meteorites (Durda and Flynn, 1999; Flynn et al., 2005; Durda et al., 2011). The few strength measurements performed (Kimberley and Ramesh, 2011) leave open the question of statistical variation of meteorite strength, and the scale variation relevant to asteroid materials.

In order to provide the data necessary to understand or predict the physical and rheological properties up to hundreds-of-meter scales, we undertook repeated destructive measurements of two representative meteorites: Allende, a CV3 carbonaceous chondrite (a primitive Solar System material), and Tamdakht, an H5 ordinary chondrite (typical of the common asteroids in near-Earth orbit (Binzel et al., 1996)). Both meteorites are observed falls. Tamdakht was observed in 2008 over Morocco while Allende was observed in 1969 over Mexico. Both meteorites were recovered immediately after the falls and have been curated ever since. Neither the Tamdakht nor the Allende meteorites show signs of terrestrial weathering. Suitable pieces of Allende are light grey with abundant chondrules and CAIs (calcium-aluminum-rich inclusions). Tamdakht, with a shock grade of S3, exhibits a heterogeneous structure criss-crossed with shock veins and centimeter-sized regions of white (lower shock) and light grey (more highly shocked) matrix. Chondrules are visible but largely integrated into the matrix through extraterrestrial metamorphism. Quasistatic unconfined compression experiments were conducted on ten and thirteen centimeter-sized cubes of Allende and Tamdakht, respectively. The disrupted fragments are preserved for ongoing analysis, including studies of disruption surface morphology and forthcoming microgravity spaceflight experiments (Asphaug and Thanga, 2014).

2. Materials and methods

We conducted our measurements on ten Allende cubes ranging from 0.7-cm to 4.4-cm and on thirteen Tamdakht cubes ranging from 1- to 3-cm. Elastic wave velocity measurements were performed using a manually controlled Olympus 5077 PR electric pulse generator/receiver which is used to generate and pre-amplify the electric pulse sent to the transducer and also performs band-pass filtering to help clean up scatter noise from the received signal. Pairs of Olympus V-110RM full contact through transmission longitudinal wave transducers and V156-RM full contact normal incidence shear wave transducers were used as the sensor/actuator pair. To decrease the necessary contact pressure required to be applied on the meteorite surface and signal attenuation in between interfaces, an Olympus shear wave coupling fluid was used in between the meteorite surface and the sensor/actuator pair. A National Instrument PI-1042 Digital Acquisition system was used to acquire the signal data on a desktop computer and the National Instrument NIScope software was used as a virtual oscilloscope.

As per the Olympus equipment specifications state, samples may be of any geometry that permits clean pulse/echo measurement of sound transit time through a section on thickness. Ideally this would be a sample at least 1.25 cm thick, with smooth parallel surfaces and a width or diameter greater than the diameter of the transducer being used. However, it is recommended that the samples be at least 0.5 cm thick and therefore measurements were obtained for all samples, except for one Allende cube whose compression test was performed before the sound speed equipment was obtained. Measurements were obtained two to four times per side of the samples to account for any anisotropy. All subsequent data analysis and arrival time calculations were performed using LabView and Matlab.

The Uniaxial compression tests for most of the specimens were performed on an Instron 5985 frame with a 250 kN load cell and compression fixtures comprising of 145 mm diameter radial platens with a maximum rated load of 100 kN. Since the Tamdakht specimens with dimensions greater than 1 cm were expected to take more than 100 kN of load, they were tested on radial platens with a diameter of 165 mm and a maximum rated load of 300 kN. All tests were conducted at room temperature and in displacement control with a displacement rate of 0.25 mm per minute to ensure quasi-static conditions. The GOM ARAMIS 5M, a 3D Digital Image Correlation (DIC) system that enables noncontact measurement of displacement and strain fields is also used. This system is particularly suitable for full field 3D deformation and strain measurements under static and dynamic loading. To prepare the specimen for measurements using the DIC system, a random speckle pattern is applied on the surface of the samples by using an opaque white and black color spray. A stochastic spray pattern is critical in tracking the displacements of the speckled dots, especially in small cubic samples. Strains are thus calculated using the inbuilt Instron extensometer as well as with the DIC system. For those specimens with multiple peaks of failure, the maximum strength was that of the peak with less than two percent change with the initial slope.

The Elastic Modulus E is derived from the sound speed measurements given:

$$E = \frac{V_L^2 \rho (1+\nu)(1-2\nu)}{1-\nu} \tag{1}$$

where ρ is the density, V_L and V_S are the longitudinal and shear wave speeds and ν is the Poisson's ration given by:

$$\nu = \frac{1-2\left(\frac{V_S}{V_L}\right)^2}{2-2\left(\frac{V_S}{V_L}\right)^2} \tag{2}$$

The Elastic Modulus was also derived directly from the compression measurements. Logarithmic strains in the loading direction were calculated using DIC and the stresses and force readings were obtained from the load cell. A linear model was then fitted to the linear portion of the stress strain curve and the slope of the curve was taken to be the Elastic Modulus in the loading direction. Generally the Elastic Modulus derived from these two different methods is within an eleven percent difference in average except for a few outliers. This ensures that although the specifications of the ultrasonic equipment states that ideally specimens should be greater than 1.25 cm, the recommended dimension of 0.5 cm provides accurate results.

3. Results and discussion

Elastic moduli were measured prior to disruption for each cube (see Table 1), viz., Allende $E = 16.66 \pm 4.72$ GPa and Tamdakht, 21.01 ± 6.57 GPa. During disruption the meteorites showed generally uniform deformation in the axial and lateral direction until lateral deformation caused cracks to grow parallel to the load path. Under loading, the cracks likely began from preexisting heterogeneities that produced stress concentrations and grew with increase in lateral deformation leading to axial separation of the specimen at final failure. Shear banding was not observed, though there was lineation on the fracture surfaces parallel to the axial direction. Under compression, Allende cubes developed several competing cracks at low deformations. At higher deformations a single major crack often led to material failure (see Fig. 1). Tamdakht cubes retained