Characterising Shock Propagation through Inert Beds

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Abstract. Studies of granular materials have indicated that non-steady shock behaviour can arise over short distances when they are dynamically compacted. Unlike continuous materials, granular powders undergo irreversible compaction, which leads to hysteresis during the unloading phase. In this study, ultrafine sucrose with a mean particle size of $8\mu m$ was subjected to a planar shock from plate impact. Photonic Doppler Velocimetry (PDV) was used to measure the velocity history of the rear surface, and an evaporated make-trigger to measure the time-of-arrival on the front surface, which together allowed some elements of the shock's behaviour inside the bed to be deduced. Non-steady behaviour was indicated by the rise time and the average velocity of the shock varying with bed thickness. The effect of the thickness of the bed on the shock also extended to the release; thinner beds exhibited a more elastic rarefaction.

INTRODUCTION

Low density powdered explosives are used in electrical detonators, which have a wide range of applications. To better understand the first stage of their mechanism it is necessary to understand how the explosive behaves when a shock is imparted. Isolating the initial shock response from the subsequent detonation can be difficult, and so an inert simulant is used to remove the effect of chemical reaction. Coarse and fine grained sugar have previously been used to simulate HMX [1] [2]. Similar shock propagation velocities and wave dispersion were found for both substances. The dispersion was found to be controlled by particle size, and not dependent on density or chemical reactions, leading to speculation that crystal fracture was responsible. Prior work on shock compaction of glass microspheres identified a precursor wave, implying a densification mechanism occurs via particle rearrangement, fracture, or both [3]. The objective of this study was to determine the response of an ultrafine powder to a shock to see if it is a suitable candidate as an inert simulant for a high explosive. This information will be used to guide future research into detonator function.

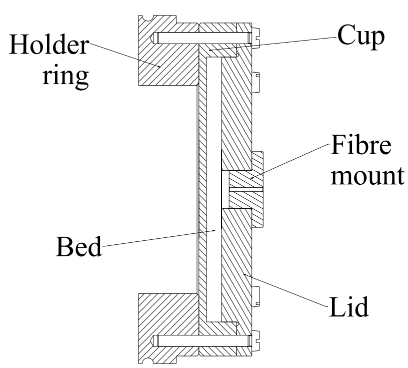

FIGURE 1. Cross-section of the sample cell. The cup, lid and fibre mount are all PMMA while the holder ring is aluminium. The cell was originally designed for studying sand [4]

EXPERIMENTAL

An ultrafine icing sugar sold commercially as ‘Silk Sugar’ was chosen as the subject material. The manufacturer specifies the mean particle size is $8\mu m$, with 50% of particles between $7.5\mu m$ and $10.5\mu m$. The sugar was contained in a PMMA cell as shown in Fig. 1. The interior volume of the cell was measured and used to calculate the required mass of powder needed to produce a sample bulk density of $1.00 \pm 0.01 gcm^{-3}$ - similar to the density of PETN in exploding bridgewire (EBW) detonators.

A single-stage 2” light gas gun was used in conjunction with a $10mm$ thick copper flyer plate to impart a shock to the PMMA cell. The cell was aligned with the end of the barrel to an accuracy of approximately $1mrad$. The speed of the projectile was measured using graphite pins at the end of the barrel to within 1%.

A make-trigger consisting of two $100nm$ thick copper pads evaporated onto the front surface of the cell gave the arrival time of the projectile. A single mode PDV system using a $40mW$, $1550nm$ laser was integrated into the cell with a fibre mounted on the rear surface. A reflective surface was provided by a thin disc of copper sheet in contact with the sugar. The velocity history of this free surface was found by Fourier transforming the PDV signal. The shock arrival time at the rear surface was taken to be the 50% point on the initial rise. The average shock velocity across the bed U_S was then calculated using these times and the known Hugoniots of Cu and PMMA. Between shots, the thickness of the bed was varied in order to investigate the build-up of the shock.

Standard impedance matching techniques illustrated in Fig. 2 were used to calculate the release behaviour of the front PMMA plate; the release adiabat in PMMA is assumed to be the shock Hugoniot reflected about the particle velocity. The measured shock velocity and initial density gives the Rayleigh line, which must intercept the PMMA release adiabat at the particle velocity at the interface. The free surface velocity as measured by PDV is the (negative) release velocity in the sugar’s Lagrangian frame, therefore the release speed u_R is found by reflecting the free surface velocity u_F about the particle velocity u_2.

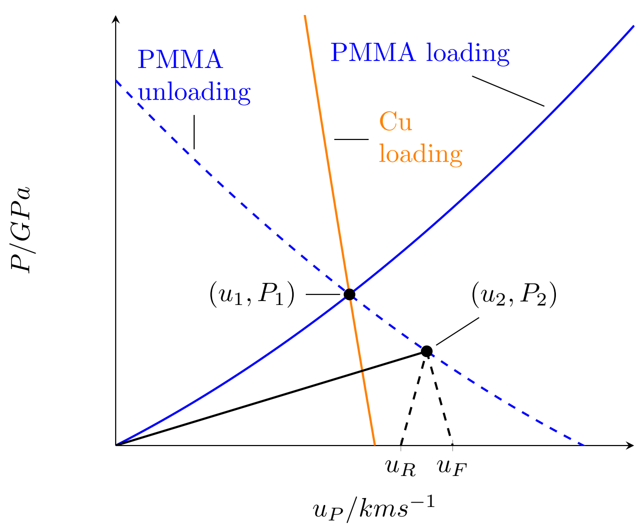

FIGURE 2. Schematic of the impedance matching technique used to derive the particle and release velocities [5]. The marked coordinates are the states at the flyer-PMMA interface and the PMMA-sugar interface respectively. u_R and u_F refer to the release velocity and the free surface velocity respectively.

The point (u_2, P_2), which describes the shocked sugar, is found by solving the two equations:

$$P = \rho_0 c_0 (2u_1 - u) + \rho_0 s (2u_1 - u)^2 \tag{1}$$

which describes the release of the PMMA in terms of the unshocked density ρ_0 and sound speed c_0, and

$$P = \rho_0' U_S u \tag{2}$$

which is the Rayleigh line to the shocked state of the sugar in terms of the shock speed U_S and the bulk density ρ_0'.

The dispersion of the wave was investigated by measuring the rise time of the shock, which was taken to be the time for the free surface velocity to go from 10% to 90% of its plateau value. For some shots a second plateau was observed some time after the first; this was suggested to be due to the copper mirror losing contact with the bed.

RESULTS AND DISCUSSION

Seven shots were conducted, with the aim being to have the same impact velocity each time. This was the case, with a velocity of $501 \pm 5ms^{-1}$. Figure 3 shows the average shock velocity U_S increasing as a function of bed thickness. This relation implies that there is a run-up phase where the shock is accelerating. Compaction ahead of the wave would produce a denser region, through which the wave would travel at a higher speed. In thicker beds the wave is travelling in a denser region for a greater proportion of the total travel time, therefore the average shock speed is greater. The amount of scatter leads us to believe that the shock speed is very sensitive to small changes in the internal bed structure.

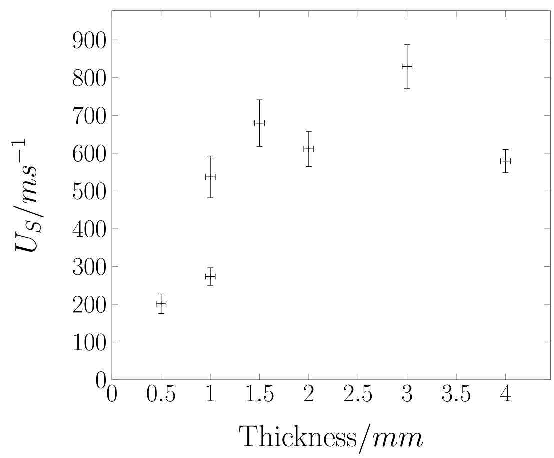

FIGURE 3. Shock velocities calculated from arrival times, taking into account the delay introduced by the front of the PMMA cell

Figure 4 shows the rise times of the five shots for which the signal-to-noise ratio of the PDV was high enough to allow a clear rise to be distinguished. The thickness of the shock front increases with the bed thickness. A force-chain argument can explain this trend: the time for an initial force to be transmitted across the bed depends on the length of the force chains spanning the bed. Thicker beds can support a wider distribution of chain lengths, resulting in a more smeared out wave front.

The release velocity u_R can be inferred from the plateau of the velocity history u_F. A release path with a shallower gradient and a lower velocity zero pressure point indicates that the effect of elastic reassertion is greater [6]. It was found that thinner beds have a shallower release gradient, suggesting that the effect of shock compression was mainly to elastically compress individual particles. Thicker beds, which were dominated by irreversible compaction, exhibited a steeper release gradient. The mechanism behind this compaction is likely due mainly to particle rearrangement causing pore collapse, however, there may also be a degree of fracture into smaller particles. This compaction is probably facilitated by an increase in particle mobility as the bed size increases.

CONCLUSIONS

Plate impact was used to shock load beds of varying thicknesses of sugar, and the response measured using PDV. Evidence of non-steady behaviour was observed, which manifested as an increasing shock velocity and rise time with thickness. The release behaviour is believed to be governed by the amount of irreversible compaction by the shock as opposed to elastic compression. Thicker beds allow for more inelastic behaviour so the unloading phase recovers less energy from the compressed powder. Further work will involve laser flyers to produce planar shocks at a smaller scale.

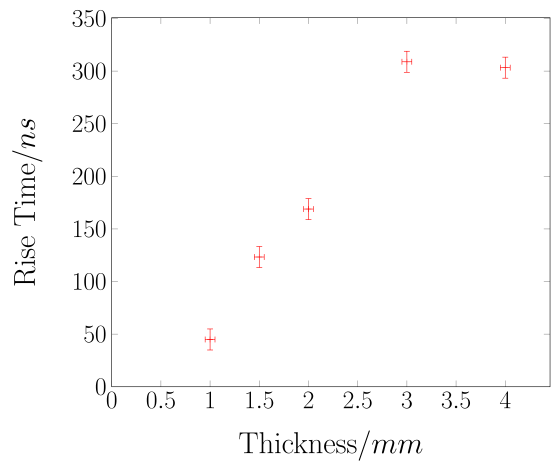

FIGURE 4. The rise time, calculated as the time for the free surface velocity to go from 10% of maximum to 90% of maximum.

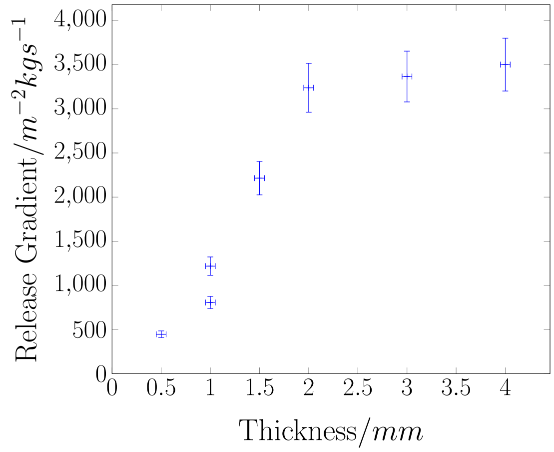

FIGURE 5. The release path of each shot from the shocked state to the zero pressure state was calculated. The shallower the gradient the more the bed reasserts during unloading.

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