A comparison of multiple techniques for determining the shock release behaviour of copper

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Abstract. A shock compression pulse normally consists of a discontinuous rise in stress or pressure followed by a sustained period, if loaded using a technique such as plate impact, and terminated with a release back to ambient conditions over a finite time. This release behaviour is a compound effect, normally dependent upon the initial shock loading conditions and the distance within the subject material that the subsequent release effect has travelled. We discuss recent work undertaken on the development and testing of two experimental methodologies for investigating the release behaviour. These methods were employed to determine the release behaviour of high-purity oxygen-free copper.

1. Introduction
When a material is compressed, either by a discontinuous shock or continuous ramp loading, there is a change in the state variables which can be measured or calculated in order to create an equation of state. Over the years compendia of these measurements have been collated for many different materials [1,2,3,4]. Whilst these compendia provide a large body of data on the shock compression response of materials, they do not significantly address the release behaviour, which has been studied less extensively [5,6,7].

Work has been recently undertaken to develop an experimental approach to measure the release path of a shocked material via the method of calculating points of partial-release along the release path. This paper will detail the latest iteration of this experimental development. Additionally, Rothman [8] recently reported work on using a characteristics method to apply corrections to a measurement of release wave propagation measured through a windowed interface. This has been included into the experimental configuration and allows a comparison between the two methodologies.

2. Experimental Description
There are in effect two impact experiments combined within a single target arrangement. The first is denoted as the partial-release technique which uses a selection of materials of lower shock impedance than the material under test, bonded to the rear to create an array of partial-release states in the copper. By equating the partial-release state in the target material to the shock state in the backing component via impedance matching it is possible to build up multiple points on the target release path. The target consists of a 3 mm thickness 140 mm diameter high-purity oxygen-free copper target disc impacted by a 3 mm thickness copper impactor matched to the target. The backing materials consisted of 18 mm diameter, 3 mm thickness discs of: Ti-6Al-4V titanium alloy, AZ61 magnesium alloy, vanadium, zinc
and PCTFE (poly-chlorotrifluoroethylene or Kel-F), attached to the rear of the copper target plate using a low viscosity epoxy.

![Diagram of target plate rear surface showing multiple backing discs, angled PMMA windows and piezoelectric contact pins.](image)

**Figure 1.** Schematic of target plate rear surface showing multiple backing discs, angled PMMA windows and piezoelectric contact pins.

The secondary technique we refer to as the release-wave propagation technique. This uses the propagating release from the rear of the impactor to infer a Lagrangian sound speed upon release and in turn to calculate the release adiabat. The release profile is measured through a window at two measurement thicknesses by use of a machined spigot on the rear of the target disc. To maintain a shock pressure at the measurement locations on the rear of the target disc and spigot a window is attached at both locations. The window was either single-crystal lithium fluoride (LiF) or polymethyl methacrylate (PMMA). The LiF window had an anti-reflective coating applied for 1550 nm and the PMMA window had an 8° angled rear surface to minimise secondary reflections. The target arrangement is illustrated in figure 1.

An array of eight piezoelectric time-of-arrival pins were attached flush with the impact face in order to provide an accurate measure of the impactor tilt at time of impact. The projectile consisted of a polycarbonate sabot with the copper impactor bonded onto the front face. The shots were fired using the large bore single-stage gas gun located at the Institute of Shock Physics, Imperial College London. This facility can utilise a 100 mm diameter projectile allowing larger shocked areas and longer duration events to be investigated. The shock states in the backing materials and the window interface velocities were interrogated using a multichannel frequency-shifted photonic Doppler velocimeter (PDV). Raw PDV data for the through-window measurements were corrected using a suitable linear refractive-index correction [9]. A linear correction factor of 0.9889 was applied for the through PCTFE measurement. A secondary single-channel PDV system was used to record the projectile velocity before impact.

### 3. Data Analysis Methodology

The measured PDV velocity-time profiles were converted to in-situ particle velocity, $u_p(t)$, by the method of characteristics described by Rothman and Maw [10] using a Steinberg equation of state [2] for the window material.
The Lagrangian sound speeds, $c_L(u_p)$, were then found by three methods: using the in-situ velocity-time profiles, $u_{p1}(t_1)$ and $u_{p2}(t_2)$, for both steps, of thickness $h_1$ and $h_2$:

$$c_L(u_p) = \frac{(h_2 - h_1)}{t_2(u_p) - t_1(u_p)}$$  \hspace{1cm} (1)

by using the velocity-time of either step, giving two sets of sound-speed data, and the time, $t_0$, of the release launch at the flyer (thickness $h_f$) rear,

$$c_L(u_p) = \frac{(h_f + h_1)}{t_1(u_p) + t_0}$$  \hspace{1cm} (2)

and by a linear fit to the release launch time ($t_0$) and the times of arrival of a particle velocity at the steps; $(t_0,t_1(u_p),t_2(u_p))$ against the Lagrangian coordinates ($-h_f,h_1,h_2$). The sound speed was the reciprocal of the gradient.

Release launch time was calculated from the step and flyer thicknesses and the shock velocity calculated from the arrival time at each step. Sound speed as a function of the particle velocity was then integrated to $P(V)$ on the quasi-isentrope from

$$dp = \rho_0c_L(u_p)du_p$$  \hspace{1cm} (3)

$$dV = -\frac{du_p}{\rho_0c_L(u_p)}$$  \hspace{1cm} (4)

and the characteristics correction was then iterated using the newly-generated $P(V)$ until convergence. Ideally all methods should generate identical adiabats. Any variation is due to errors in the characteristics corrections from non-unique wave speeds arising from strength effects.

4. Results

Currently four experiments have been conducted in the trial series to date. Two experiments were fired at nominal velocities of 700 m/s and 900 m/s using a LiF window, with these then repeated changing the window to PMMA for the purpose of testing that the characteristics correction from interface velocity to in-situ velocity was independent of the window material chosen. Uncertainties in velocity history are taken from the statistical error in the rear surface or interface velocity profiles.

Table 1. Projectile velocities and window materials for each shot.

| Shot  | Projectile Velocity (m/s) | Impactor | Window Material |
|-------|---------------------------|----------|-----------------|
| STD3-1| 901.2 ± 0.5               | Copper   | LiF             |
| STD3-2| 703.0 ± 0.2               | Copper   | LiF             |
| STD3-5| 690.1 ± 0.5               | Copper   | PMMA            |
| STD3-6| 903.2 ± 0.2               | Copper   | PMMA            |

The pressure values are calculated by referring the particle velocity, inferred from either the free surface velocity or measured directly, to a fully elastic-plastic Hugoniot which have been constructed for each backing material using the compendia of Marsh [1] and Steinberg [2] to provide the equation of state and elastic limit parameters.

Table 2. Shock states reached for each backing material for shot STD3-1.

| Material | Particle velocity (mm/µs) | Stress (GPa) |
|----------|---------------------------|--------------|
| No backing | 0.896 ± 0.002         | nil          |
| Vanadium       | 0.480 ± 0.002       | 17.03 ± 0.06 |
| Ti-6Al-4V       | 0.537 ± 0.001       | 14.15 ± 0.02 |
| Zinc             | 0.526 ± 0.006       | 14.55 ± 0.17 |
| AZ61 Mg         | 0.701 ± 0.001       | 6.95 ± 0.01  |
| PCTFE            | 0.740 ± 0.015       | 5.20 ± 0.10  |
| LiF A            | 0.633 ± 0.003       | 10.30 ± 0.04 |
| LiF B            | 0.633 ± 0.007       | 10.30 ± 0.12 |
The release points calculated using the partial-release technique for all four shots conducted to date are shown in figure 2. There is a small disagreement between the two shots fired at a nominal projectile velocity of 700 m/s which is due to the difference in the actual projectile velocity of 13 m/s.

**Figure 2.** Backing material Hugoniots and measured release states for all four shots.

As mentioned in section 3, there are three ways of measuring the Lagrangian sound speed upon release from the two measurement points and the initial release point at the rear of the impactor. These give four differing sound speeds, and are charted together and shown in figure 4 for shot STD3-1. There is a small variation between the four speeds, possibly due to uncertainties in the experimental thicknesses and timing points. Strength is apparent in the transition from bulk to higher elastic velocity at higher particle velocity, of greater than around 0.35 mm/µs for all four sound speeds.

**Figure 3.** The velocity histories at the two Lagrangian locations, $h_1$ and $h_2$ for shot STD3-1 through a LiF window.

**Figure 4.** Lagrangian sound speeds measured for shot STD3-1. The four differing results are from the combinations of loci discussed in section 3.

5. **Discussion**

Although the results look promising it should be appreciated that using the free surface velocity to calculate the in-situ particle velocity is an approximation and as such there is an inherent variation
between the actual shock state and our approximated shock state. The magnitude of this variation will differ for each backing material dependent upon the materials’ individual shock response and strength. This limitation can be mitigated by using transparent windows as the backing materials. With these the particle velocity can be measured directly at the target/window interface, however the number of materials available for use as windows in limited.

During the design of the experiment it was expected that the PCTFE disc was too opaque with a 3 mm thickness to allow the transmission of sufficient light to see an interface velocity. Since the interface velocity has been recorded there is now a necessity to investigate the shock-induced changes to the refractive index and to enumerate a linear correction factor for PCTFE. This value was determined experimentally to be 0.9889 for a 1550 nm wavelength. The partial-release technique is also sensitive to the accuracy of the Hugoniot of the chosen backing materials and the resolution of the release path is limited by which and how many backing materials are chosen.

Calculating the adiabat from the release sound speeds has shown a good result. The adiabat however has not been calculated to full release due to only a partial-release being generated from the rear of the impactor. Despite these limitations the experiment has shown good agreement between the two techniques. Figure 5. Both the calculated release adiabat and the partial-release states for shot STD3-1 are shown together showing a good agreement between the two techniques.

6. Conclusions
We have demonstrated two methodologies for the measurement of release paths in high-purity copper. Each technique has its limitations but by combining the two within a single configuration it is possible to enhance confidence in the measured release points. Further work is planned to validate the technique for materials with a non-negligible elastic-plastic response with the aim of increasing the fidelity to determine phase change or other crystallographic effects along the release path.

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