A view on the functioning mechanism of EBW detonators - part 2: bridgewire output

E A Lee, R C Drake and J Richardson
Atomic Weapons Establishment, Reading, Berkshire, RG7 4PR, United Kingdom
E-mail: elizabeth.lee@awe.co.uk

Abstract. This is the second paper of three papers describing the studies to identify the initiating mechanisms in Exploding Bridgewire (EBW) detonators. In this paper the results of experiments to quantify the effect of the bridgewire explosion are described. Experiments have been performed to characterise the output from the bridgewire in terms of the stimulus it would apply to the surrounding explosive in an EBW detonator. The expansion speed of the bridgewire at burst as a function of input energy has been measured using Photonic Doppler Velocimetry (PDV). To complement the bridgewire expansion velocity determinations aquarium experiments were carried out in which the shock wave velocity in water was measured, as a function of energy, by high speed photography. The shock pressures were calculated and compared to initiation criteria for PETN.

1. Introduction
The first paper in the series [1] reported on the electrical characterisation of the bridgewire; the energy required to burst the bridgewire was determined. This paper looks at the next stage of the energy transfer in an EBW detonator, the output from the bridgewire when it explodes.

Experiments were performed to characterise the output of an exploding bridgewire to assess if they were sufficient to shock initiate PETN EBW detonators without contributions from other processes. The experimental characterisation comprised the measurement of the:
- expansion speed of unconfined bridgewires
- peak pressures in a confined medium (water)

2. Firing Configurations
The same fireset was used for all the experiments described in this paper. It was a high voltage, capacitor (50 nF) discharge based system fitted with a current monitor fitted to the output. The energy delivered to the bridgewire was varied by charging the fireset capacitor to different voltages. Thus, the relationship between the delivered energy and the parameters describing the bridgewire explosion effects could be determined.

A purpose built current monitoring system (a wrap-around double transformer) was incorporated into the firing system to enable the other diagnostic systems, described below, to be correlated to the firing signal and the condition of the bridgewire, in particular, the time of bridgewire burst. From studies on PETN based EBW detonators the energies corresponding to the threshold and all fire levels for this system were determined. These values were used to relate the results in this paper to detonator performances.
3. Expansion Speeds of Unconfined Bridgewires: Experimental
Photonic Doppler Velocimetry (PDV) was selected to measure the expansion of bridgewires as it is a non-intrusive technique which is capable of measuring the movement of very small areas (a key feature given the sub millimetre bridgewires used in this study). A more detailed description of the system is given elsewhere [2, 3].

Initial experiments gave variable results which were attributed to the alignment of the PDV probes with the bridgewires and the focussing of the PDV laser onto the bridgewires. A visible laser was coupled to the PDV probes to enable, with the aid of a microscope, the PDV probes to be positioned so that the laser beam was focused on the middle of the bridgewires. The PDV probes used in these studies were focussing probes with a spot size of 18 µm and a focal length of 14 mm.

The PDV and current monitoring systems were time correlated. This involved calculating the time delay in the current monitoring cables by applying a 5 ns/m signal speed to the measured cable length. The time delay in the PDV system was evaluated by using a swept frequency time domain reflectometer (Luna Technologies OBR4600 Optical Backscatter Reflectometer).

4. Expansion Speeds of Unconfined Bridgewires: Results and Discussion
At firing energies corresponding to the “all fire” regime the PDV traces all had a very narrow pulse peaking at a velocity of 3000 m/s; the peak velocity was dependent on the bridgewire material. Following the pulse, for a period of around 500 ns, there were no data. It is believed that the lack of data is a consequence of the plasma acting as a black body. After this period there was a long duration signal (of at least 2 µs) of multiple lower velocities up to a maximum velocity of about 200 m/s, see figure 1. The “cloud” of multiple velocities is attributed to the breakup of the bridgewire into particles. These occur to late to be of significance to the initiation of the explosive or performance of the detonator.

![Figure 1. Example PDV trace for a bridgewire fired at all-fire voltage.](image)

Firings at energies around the 50% threshold level had PDV traces with a fast rising pulse with rise times of around 200 ns. Unlike the pulses recorded at all-fire energies the rise times were slower and there were slow decaying tails. Once again, after 500 ns, there were a “cloud” of lower velocities, see figure 2.
When bridgewires were fired at energies below that required to burst the bridgewires, a range of velocities were detected. The peak values were of the order of 1500 m/s and were achieved in about 300 ns. The velocities decreased to about 500 m/s in around 2 μs, see figure 3. By analogy with the work of Karioris et al [4], who reported recovering an aerosol of fine metal particles post explosion of bridgewires, it is postulated that in the sub-bridgewire explosion regime only vaporisation occurs.

The firing current-time profiles were time correlated to the PDV data. By comparing the PDV spectrograms with the corresponding current profile it was apparent that, as expected, the peak velocity coincided with the bridgewire burst time. In figure 4 the firing times and the bridgewire expansion peak velocities are plotted as a function of energy and it can be seen that they display reciprocal trends: increasing the firing energy increases the bridgewire expansion velocity and decreases the firing time. From the asymptotic behaviour of the detonator firing time curve the minimum bridgewire expansion velocity can be derived. The values so derived are of the order of a
few mm/μs and are consistent with the impact velocities required for shock initiation. These are preliminary results and further studies are in progress to further explore these trends.

5. Expansion Speeds of Confined Bridgewires: Experimental
The current-time profiles of unconfined and confined bridgewires are different with the difference being most noticeable at bridgewire burst. The peak bridgewire expansion velocities are at the time of bridgewire burst. Therefore, to understand the effect of confinement, bridgewires were exploded in water and the propagation of the shock waves (in the water) characterised.

The experiments were based on a purpose built tank (aquarium), based on the design used by Frank and Gathers [5]. They were made of optical glass with a port into which bridged headers could be sealed. The volume of an aquarium was 3 cm$^3$.

To capture the propagation of the shock waves in the water the aquarium was back-lit with a laser. A x12 (Navatar) lens was used to image the configuration onto a high speed framing camera (Specialised Imaging SIM8). For each experiment the framing camera recorded eight images with an inter-frame time of 68 ns and an exposure time of 7 ns. The experimental configuration is shown in figure 5.

![Figure 5. Aquarium Test Experimental Set-Up.](image-url)
The bridges were fired using the same fireset and over the same range of energies as that used in the unconfined bridgewire expansion velocity experiments described above.

6. Expansion Speeds of Confined Bridgewires: Results and Discussion

For energies above those that would be required to detonate PETN a typical sequence of frames is shown in figure 6. In figure 6 the order of the frames is indicated by approximate frame time (from start of current flow). The glow seen clearly in frame 1 is the laser back light. In the second frame the glow of the bridgewire is evident (caused by melt and/or vaporisation of the material), as is the lack of significant expansion. A single shock wave propagating radially outwards, from the centre of the bridgewire, is seen in the subsequent frames.

![Figure 6. Typical Framing Camera Records of Bridgewire Explosion in Water.](image)

The frames were analysed as follows. The dimensions of each image were determined using the length of the bridgewire. The leading edges of the shock waves were detected and marked. The shock wave location data were re-sampled to 1000 points by a shape preserving spline fit for each frame. The distance travelled between frames was determined. From the distance travelled and the inter-frame time the shock velocity was determined.

Application of the Rankine-Hugoniot equations together with the constants (for sound speed) given by Cooper and Kurowski [6] enabled the shock pressures to be determined. The shock pressures were then extrapolated to the bridgewire burst times. At firing energies above the all-fire level the pressures generated by the bridgewires were approximately constant with a value of 1.5 GPa. This value can be put into context by consideration of the Pop-plot.

Pop-plot data [7] are based on 1-dimensional, sustained shocks whereas bridgewires generate highly divergent, finite duration shocks. Therefore, for a given pressure, the run to detonation distance will be greater for an exploding bridgewire generated pressure than that predicted by the Pop-plot. However, Pop-plot data can be used to support qualitative judgements. For PETN, at a density of 1.0 g/cm$^3$, published Pop-plot data predict a run to detonation distance of the order 10 µm for a shock pressure of 1.5 GPa. The predicted run to detonation distance is sufficiently small that, even if divergence effects increase the run to detonation distance by an order of magnitude, it is credible that the functioning mechanism of EBW detonators is by shock initiation without the need to invoke contributions from other mechanisms.
7. Conclusion
To understand the initiation mechanism in exploding bridgewire detonators the output characteristics of exploding bridgewires have been determined. The magnitude, with fireset energy, of bridgewire expansion velocities and output pressures support shock initiation being a credible mechanism in the initiation of the explosive in EBW detonators.

8. Acknowledgements
The authors would like to thank for Mike Bowden, Sarah Pantaleon-Knowles and Scott Aitken for their assistance in applying PDV to the measurement of the bridgewire expansion speeds and the set-up of the framing camera.

References
[1] Lee E A, Drake R C and Richardson J 2013 A view on the functioning mechanism of EBW detonators – part 1: electrical characterisation Submitted to these proceedings
[2] Bowden M D and Maisey M P 2007 The development of a heterodyne velocimeter system for use in sub-microsecond time regimes Proc. SPIE 6662 Optical Technologies for Arming, Safing Fuzing & Firing III 10
[3] Dolan D H 2010 PDV modifications PDV Users Workshop Ohio (available at http://hdl.handle.net/1811/52726)
[4] Karioris F G, et al 1962 Aerosols from exploding wires Exploding Wires (Plenum) vol 2 eds Chace and Moore pp 299-312
[5] Frank A M and Gathers G R 1989 Shock pressure determination in detonator wires Lawrence Livermore National Laboratory Tech. Rep. UCRL-100687
[6] Cooper P W and Kurowski S R 1996 Introduction to the technology of explosives (Wiley-VCH) p 66
[7] Gibbs T R and Popalato A 1980 LASL Explosive Property Data Part I (University of California Press) 4 291