A view on the functioning mechanism of EBW detonators - part 3: explosive initiation characterisation

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Abstract. This paper is the third of three looking at the initiation of PETN in an exploding bridgewire detonator. The energy flow from the fireset through the bridgewire has been characterised and the probable input to the low density PETN determined. These earlier studies showed that shock initiation remained a credible mechanism for an exploding bridgewire detonator. This final set of experiments was designed to compare and contrast the shock initiation of low density PETN, by both a slapper detonator and a shock sensitivity test, with exploding bridgewire initiation. The function and lost times of slapper and EBW detonators were compared to one another to allow the credibility of a shock initiation mechanism to be further assessed. The results of the experimental work will be presented, together with a potential step-by-step initiation mechanism for a PETN exploding bridgewire detonator. The proposed mechanism is based on the energy flow through the detonator system and the affect of varying the input energy on the detonator function time.

1. Introduction

In Part two of this three part study the output from an exploding bridgewire was characterised in terms of the bridgewire expansion speed and shock pressure [1]. From these studies it was concluded that the bridgewire expansion speed and shock pressure are of a sufficient magnitude that shock initiation of PETN is credible.

In this study experiments were carried out to understand the effect of density on the shock initiation of PETN by comparing the initiation of high (1.6 g/cm^3) and low (1.0 g/cm^3) density PETN using an exploding foil header. By comparing the functioning characteristics of low density PETN initiated by exploding bridgewire and foil headers the role of shock initiation in EBW detonators was assessed.

2. Detonator Manufacture

The EFI and EBW detonators used in this study were both based on a common design. The detonator body was a cylindrical can. For the exploding foil detonators a backing plate was placed over one end and the PETN pressed into the can to the required density. The backing plate was then removed and the detonator can mated to a standard exploding foil header. The EBW detonators were fabricated by mating the detonator can to the header (containing the bridgewire) and the PETN pressed onto the header. In all cases the PETN charge was pressed to the same height.

3. Detonator Performance Characterisation

For the EBW detonator firings a capacitor discharge firing system (based on a 50 nF capacitor charged to 2.0 kV) was used. For the EFI detonator firings a similar firing system was used but with a 200 nF capacitor charged to 3.2 kV. For all detonator firings the burst current, time to bridgewire burst and the

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time to end event (the time at which the reaction reaches the end of the PETN compact) were measured.

The firing times were calculated by subtracting the time at which the firing current started to increase from the time to end event. To enable a direct comparison between EFI and EBW detonators the explosive time was also calculated. The explosive time is defined as the difference between the time at which energy is imparted to the PETN to the time of break out of the detonation wave from the PETN charge.

For the EBW detonator:

$$\textit{Explosive Time} = \textit{Firing Time} - \textit{Bridge Burst Time} \tag{1}$$

Whereas for the EFI detonator:

$$\textit{Explosive Time} = \textit{Firing Time} - \textit{Bridge Burst Time} - \textit{Flyer Flight Time} \tag{2}$$

In both cases the bridgewire burst time was the time corresponding to the dip in the current-time waveforms. The Flyer Flight Time was determined by firing EFI headers and measuring the flyer characteristics with a Photonic Doppler Velocimetry (PDV) technique [2].

4. Low and High Density PETN EFI Detonator Lost Times

The measured and derived parameters for the initiation of low density and high density PETN are summarised in table 1.

Table 1. EFI Detonator Experimental Firing Times.

Density (g/cm^3)	Experimental	
	Firing Time (μs)	Explosive Time (μs)
1.6	0.96	0.82
1.0	1.83	1.69

It can be seen that the firing and explosive times decrease with increasing density. To rationalise the data a number of factors must be considered:

- Although the flyer impact velocities were the same in all experiments the pressure imparted to the low density PETN would be lower than that imparted in the high density PETN due to the differences in the shock impedances.
- From Pop plots [3] for PETN at different densities it is seen that, for the same pressure, the run to detonation distance and time decrease with decreasing density
- The velocity of detonation increases with increasing density.

The first two factors affect the growth to detonation and are opposing effects whereas the last factor affects the detonation propagation. To quantify these effects impedance matching calculations and Pop plot data [3] were used to calculate the run to detonation and times, see table 2.

Table 2. Calculated Propagation Times.

Density (g/cm^3)	Input Pressure (to PETN) (GPa)	Run To Detonation Distance (mm)	Run to Detonation Time (µs)	Detonation wave propagation distance (mm)	Detonation Velocity (mm/µs)	Explosive Time (µs)
1.6	19.4	0.023	0.005	5.07	7.7	0.66
1.0	7.0	0.0005	0.0001	5.00	5.5	0.93

It can be seen in these experiments, from the data presented in table 2, that the effects of the difference in the pressures and run to detonation times for the two PETN densities are insignificant compared to the effect of density on detonation velocity.

For the purposes of this paper the lost time is defined as the difference between the measured and calculated explosive times. The lost times for the high and low density PETN detonators are summarised in table 3.

Table 3. EFI Detonator Lost Times.

Density (g/cm^3)	Experimental Explosive Time (µs)	Calculated Explosive Time (µs)	Lost Time (µs)
1.6	0.82	0.66	0.16
1.0	1.69	0.93	0.76

The lost time for the low density PETN firings is significantly greater than the value for the high density but this can be rationalised. The flyer has a surface area of 0.144 mm^2 and the resulting detonation wave will be curved and so it is to be expected that the steady state detonation velocity would not be achieved until some way into the PETN charge. There is evidence that the variation of detonation velocity with wave curvature will be more pronounced as the density is reduced [4].

To assess the potential effect of wave curvature on the lost time, a detonator, was used whose cross sectional area was approximately an order of magnitude greater than that of the EFI flyer. The lost time for this initiation source was 0.9 µs which is in reasonable agreement with the value in table 3.

It is accepted that the explosive charges in EFI detonators are initiated by shock initiation. However, EFI detonators are based on explosive charges with densities in the range 1.5 to 1.6 g/cm^3. Therefore, as the initiating charges in EBW detonators have densities of around 1.0 g/cm^3 it was necessary to understand the firing characteristics of EFI detonators with PETN charges at 1.0 g/cm^3. Whilst this is not conclusive evidence it does indicate that:

- lost times increase with decreasing density,
- it is not reasonable to assume that the detonation wave propagates at the steady state detonation velocity, that is, curvature effects on the detonation velocity need to be considered in detonators.

5. Low Density EFI AND EBW Detonator Lost Times

The experiments described above established the characteristics of the shock initiation of low density cylindrical charges of PETN and provide the baseline against which to compare the characteristics of EBW initiated low density PETN and thereby assess the role of shock initiation in the functioning of EBW detonators.

The measured firing times for the EBW and EFI detonators were analysed by the application of equations (1) and (2) respectively, see table 4. The explosives times cannot be directly compared as the shock pressures from the flyer and exploding bridgewire were different and would result in different run to detonation distances.

Table 4. Comparison of Firing Characteristics for Low Density PETN EFI and EBW Detonators.

Detonator Type	Measured Firing Time (μs)	Bridge Burst Time (μs)	Flyer Flight Time (μs)	Explosive Time (μs)
EFI	1.83	0.09	0.05	1.69
EBW	2.03	0.10	N/A	1.93

From an earlier study [1] the pressure generated by the exploding bridgewire used in this detonator was experimentally determined and used to calculate the run to detonation, detonation propagation and explosive times, see table 5. There is approximately a factor of five difference between the shock pressures but the pressures are in a regime where the difference between the associated run to detonation times are small compared to the detonation propagation times. Consequently, the explosive times are, essentially, identical.

Table 5. Comparison of Propagation Times for Low Density PETN EFI and EBW Detonators.

Detonator Type	Input Pressure (to PETN) (GPa)	Run To Detonation Distance (mm)	Run to Detonation Time (μs)	Detonation wave propagation distance (mm)	Detonation Velocity (mm/μs)	Explosive Time (μs)
EFI	7.0	0.0005	0.0001	5.09	5.5	0.93
EBW	1.5	0.024	0.017	5.07	5.5	0.94

In the previous section it was established that the lost time (table 6) is determined by both the density of the explosive and the area over which the pressure is applied to the explosive. For these experiments the density for the EFI and the EBW detonators was the same. However, the areas over which the pressures were applied to the PETN charges were very different (for the EBW detonator the pressure was applied over a cylindrical surface with an area approximately a factor of 5 less than the area of the square, but curved, flyer of the EFI detonator). Therefore, detonation wave curvature effects would be expected to be greater for the EBW detonator resulting in a lost time greater than that for the EFI detonator.

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Table 6. Comparison of Lost Times for Low Density PETN EFI and EBW Detonators.

Type	Experimental Explosive Time (μs)	Calculated Explosive Time (μs)	Lost Time (μs)
EFI	1.69	0.93	0.70
EBW	1.93	0.94	0.99

6. Conclusion

It has been demonstrated that for exploding foil initiators the excess transit time, or lost time, increases with decreasing density. The excess transit times for low density PETN initiated by exploding foil and exploding bridgewire were found to be comparable. Therefore, as exploding foil initiator detonators are known to operate by a shock initiation mechanism the results in this paper infer that shock initiation is also the mechanism in exploding bridgewire detonators.

The experimental work performed across the three papers (part 1: electrical characterisation [5]; part 2: bridgewire output [1]; and part 3: explosive initiation characterisation [this paper]) suggests that the initiation mechanism of a PETN exploding bridgewire detonator can be broken down into the following steps:

- The fireset capacitor discharges, the energy flows into the system *(part 1)*.
- The bridgewire material is rapidly (100 ns) ionised by the fireset energy *(part 1)*.
- The bridge explodes. A maximum of 45% of the fireset energy is used in exploding the bridgewire *(part 1)*.
- The bridgewire explosion generates a shock with a pressure of approximately 1.5 GPa. The particle velocity has been measured as 3 mm/μs, therefore the shock velocity is assumed to be in the region of 6 mm/μs *(part 2)*.
- The output from the bridgewire does not increase significantly with increasing fireset voltage, once the fireset voltage is equal to the detonator threshold voltage *(part 2)*.
- The shock generated by the bridgewire explosion initiates the PETN *(part 2)*.
- The initial velocity is reduced due to the divergence of the initiating shock. Therefore there is significant lost time in the detonator when compared to the equivalent Pop-plot data *(part 3)*.
- The PETN detonation wave reaches steady state (‘textbook’ detonation pressure and velocity) after approximately 3 mm *(part 3)*.
- There is some evidence to suggest that the shock generated by the bridgewire explosion is supported (for up to 100 ns) by the post-burst energy (i.e. the fireset energy not used in ionising and bursting the bridgewire) entering the system *(part 3)*.

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