Detonator testing using photonic Doppler velocimetry

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Abstract:

The paper describes a method for characterization of detonator output using photonic Doppler velocimetry (PDV). Initiation of explosive charges by the shock-to-detonation transition takes place in a majority of practical applications. Successful initiation of an acceptor explosive depends on the incoming shock pressure and its duration, i.e. the energy fluence. Industrial electric detonators with copper and aluminium casing with RDX secondary charge were tested. The PDV instrumentation allowed us to obtain free surface velocity profiles at specific areas of the detonator's surface. The proposed measurement setup may also be useful for characterization of small samples of newly developed high explosives.

Keywords: Detonator, Initiation, Particle velocity, Photonic Doppler velocimetry

1. Introduction

A detonator (blasting cap) is a device which transforms a simple action such as a short electric pulse into a powerful shockwave which is strong enough to initiate detonation process in other explosives or explosive devices. Current state of the art industrial detonators consist of fusehead, optional delay element, primary explosive charge (e.g. lead azide) pressed in a reinforcing element and secondary high explosive charge ("base charge", e.g. RDX, PETN, HNS), all being confined in a metallic tube closed at one end ("shell"). The other end with the electric input wires is sealed with rubbery plastic material.

Major factors which influence initiating strength of detonators are type, mass and density of the explosive used as the base charge. It is further known that material of the shell [1], presence of the reinforcing element and shell diameter [2] influence the detonator's performance even when the same type and amount of explosive is used. Different results may also be obtained if the acceptor explosive is attached to the detonator axially (to the bottom) or radially (at the side) [3].

Testing of initiating strength of detonators is of great interest in research & development and manufacturing quality control. Several empirical test procedures such as miniature cartridge test [4], copper crusher compression test [5] or lead plate penetration test [6] have been in use within past decades. However, these tests suffer from unclear correlation between the test result and the actual initiation capability. In recent years, more complex test methods have been proposed which implement streak camera recording [7], schlieren imaging of aerial shockwave [8] and Photonic Doppler Velocimetry (PDV) [9]. The PDV is an interferometric technique which allows to record high resolution velocity-time profiles of explosively accelerated objects [10] with relatively low requirements for operator skills and moderate investment costs.

On the acceptor explosive's side, a parameter which determines its sensitivity to initiation by shock wave is the energy fluence E_f [$J \cdot cm^{-2}$]. It is defined as the amount of energy which is deposited per unit area of explosive [11]. The energy fluence is usually determined from flyer plate impact experiments using input shock pressure P, shock velocity in the unreacted explosive U, initial density of the explosive ρ_0 and shock duration t according to the equation

$$E = P^2 t / \rho_0 U \tag{1}$$

Each explosive has a certain critical value of energy fluence E_C [J·cm^{-2}] above which the initiation of detonation occurs.

This article shows free surface velocity profiles of detonator casing measured using multi-channel PDV system at particular areas of its surface and corresponding energy fluence values calculated as a kinetic energy of the shell per unit area.

2. Experimental

2.1 Materials

The detonators used in this study have been standard industrial detonators with base charge mass of 0.72±0.02 g of desensitized RDX (98.5% RDX + 1.5% wax/graphite mixture) confined in aluminium or copper shell. The density of the base charge was 1.49±0.04 g.cm^{-3}. Both aluminium and copper shells had an internal diameter of 6.2 mm, wall thickness of 0.65 mm and the base charge's column height 16 mm giving the length to diameter ratio of l/d ~ 2.5. The bottom thicknesses were 1.0 mm and 0.82 mm in the case of aluminium and copper shell, respectively [12]. It should be noted that the detonators were of industrial production quality so the particular items may slightly vary in terms of shell thickness, presence of air gaps and density of the explosive.

2.2 Experimental arrangement

The velocity profiles were measured using four channel photonic Doppler velocimeter OPTIMEX PDV (OZM Research) and electric signals produced by the PDV were recorded using high bandwidth digital oscilloscope (Tektronix DPO70000 series).

A 3D printed plastic fixture was developed to hold the tested detonator and the PDV probes. Up to four probes have been used to measure outer wall velocity profiles, one in the axial direction (bottom velocity) and three in the radial direction (side wall velocity). The radial probes were fixed in different positions (upper, middle and lower) along the base charge's column. The upper probe was pointed 1 mm below the upper end and the lower probe was pointed 4 mm above the lower end of the base charge. The PDV probes were divergent beam type made of ceramic ferrules with a polished flat fiber end face. The distances from the probe tips to the detonator surface were 5 mm and the probe angles to the surface normal were 10° (the lower and the middle probe) or 0° (the upper probe). The optimum probe angles were determined in a series of preliminary tests. The scheme of the setup is shown in figure 1.

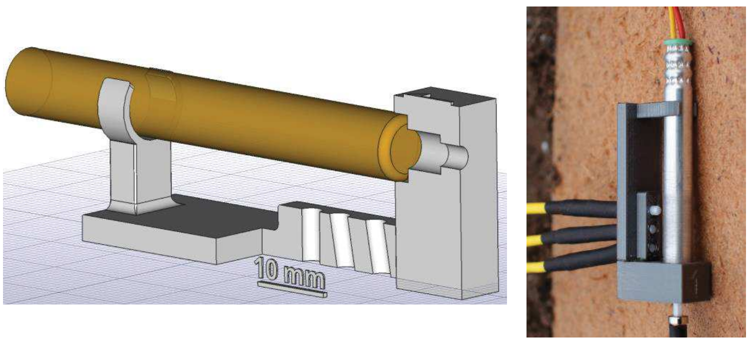

Figure 1: Scheme of the PDV measurement of the detonator free surface velocity

3. Results and discussion

3.1 Side wall velocity profiles

Two different types of velocity profiles were obtained from the axial and radial PDV probes. The detonator side wall velocity profiles (figure 2) obtained using the radial probes show stepped shape due to shock reverberations ("ringing") in the wall. It is a typical feature in the case when detonation velocity is higher than shock velocity in the wall material [13, 14]. The shell is at first accelerated by the initial shockwave and further on by expansion of detonation products so that there is a large difference between its initial and final velocity. The final velocity at the time when the wall hits the PDV probe almost reaches its maximum value before the deceleration due to air drag begins. The copper shell profiles lay below the aluminium shell profiles mostly due to their mass and shock impedance difference.

Regarding the probe position, it can be seen that although the initial step velocity is the same, the final side wall velocity at the upper and the middle probe is only 84% and 95% compared to the lower probe. Therefore the wall expansion is not in its steady state before the lower probe position.

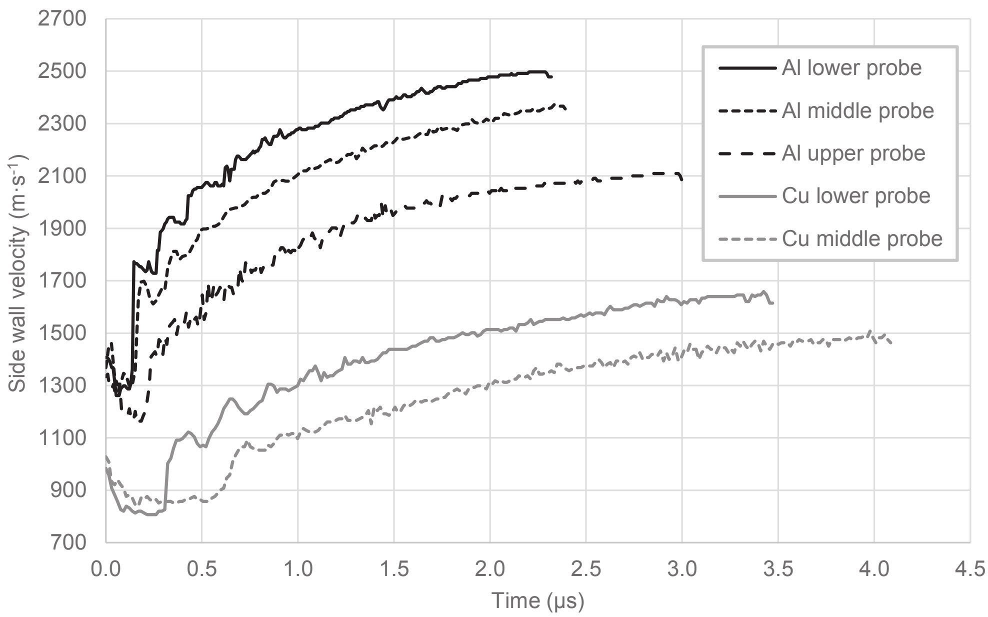

Figure 2: Typical side wall velocity profiles obtained at different positions along the detonators

3.2 Bottom velocity profiles

The bottom velocity profiles (figure 3) obtained using the axial probes have about twice the amplitude of the initial step compared to the side velocity profiles and the final velocity also does not differ much from the initial velocity. Therefore the major acceleration factor is in this case the shock wave while the contribution of gas expansion is small.

The length of the records does not correspond to the bottom to probe distance. This can be explained by too small diameter of the channel to which the bottom was accelerated. The bottom probably interacted with the plastic holder which created a cloud of particles obscuring the probe view. Another explanation is that the bottom disintegrated under the strong shockwaves because of its imperfect shape – there are manufacturer's marks on it and the shape is not completely flat.

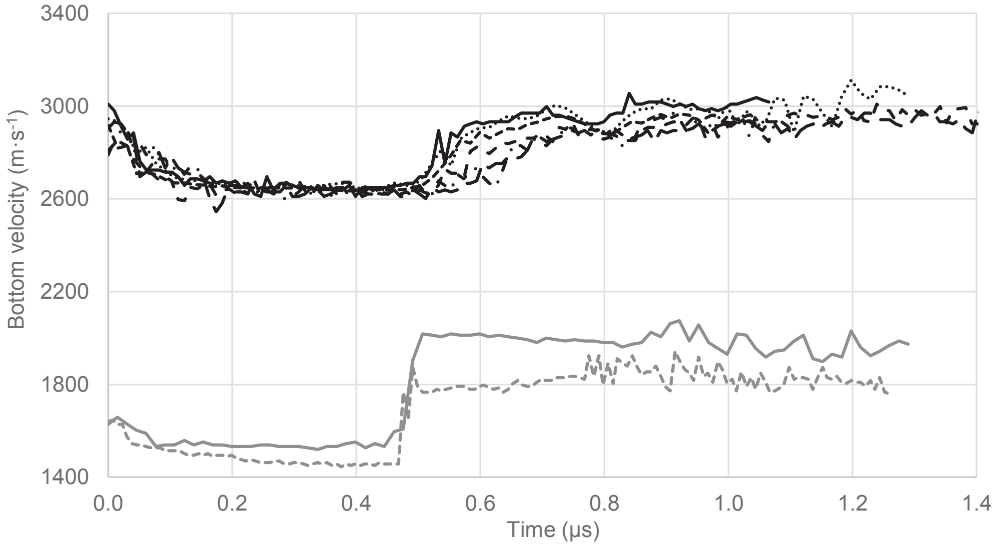

Figure 3: Bottom velocity profiles of detonators with aluminium (black) and copper (grey) shells

The time of the first shock reverberation should correspond to the thickness of the shell bottom. However there is a prolonged plateau whose duration corresponds to two roundtrip times of the shock wave in the shell bottom instead of one. It might be somehow connected to spall formation but a further clarification of this issue is needed.

3.3 Energy fluence evaluation

In the table 1, the side wall and the bottom velocities at the first velocity step and at the end of the available velocity profiles are summarized including standard deviations. The standard deviations of up to 3% may probably be attributed to the manufacturing tolerances of the detonators rather than to the measurement uncertainty. It has previously been shown that the PDV is able to reach an order of magnitude better repeatability when the tube sizes and explosive's homogeneity are strictly controlled [15, 16]. Note that six experiments have been performed with aluminium detonators but only two of them with the copper ones.

The energy fluence E_f [J·cm^{-2}] values were calculated as the kinetic energy of the detonator shell per unit area according to the equation

$$E_f = {}^1\!/_2\, m u_{fs}^2 \qquad (2)$$

where u_{fs} [m·s^{-1}] is the free surface velocity measured by the PDV probe and m [kg·cm^{-2}] is the unit area mass of the shell. The energy fluence was calculated at the first step $E_{f\text{-}0}$ and at the end of the record $E_{f\text{-}end}$. The wall thinning from 0.65 mm at the beginning down to 0.26 mm at the end of record was taken into account in the unit area mass calculation. The sum of kinetic energy E_{sum} [J] was determined using the surface area of the shell side and its bottom which were adjacent to the base charge and the corresponding values of $E_{f\text{-}end}$. It should be noted that the sum of kinetic energy only corresponds to the moment at which shell wall expanded by 5 mm so it is not in fact an exact value of total energy available from the detonator.

Keeping in mind the assumption that kinetic energy of the detonator shell is fully transferred to the explosive, the energy fluence values are to be compared to the critical energy fluence values of the explosives available in the literature [11] such as pressed PETN (16.7 J·cm^{-2}), Composition-B (184 J·cm^{-2}), melt-cast TNT (418 J·cm^{-2}), and nitromethane (1695 J·cm^{-2}).

Table 1: Summary of the wall velocity data and corresponding shock parameters

Shell	Position	$u_{fs\text{-}0}$ m·s^{-1}	$u_{fs\text{-}end}$ m·s^{-1}	$E_{f\text{-}0}$ J·cm^{-2}	$E_{f\text{-}end}$ J·cm^{-2}	E_{sum} J
Al	Bottom	2927±49	2970±40	1156	1191	1330
	Side	1364±28	2474±22	163	213	
Cu	Bottom	1650±10	1900±50	997	1322	1692
	Side	975±25	1598±48	276	295	

4. Conclusions

The free surface velocities were measured at the outer surface of the side walls and of the bottom of the aluminium and copper shell detonators. Although the aluminium shell velocities were much higher compared to the copper shells at the same distance it was found that the latter attained more kinetic energy and thus they possess more energy fluence. The only discipline where the aluminium shell detonator outclassed the copper one was the energy fluence at the bottom at the first step. Comparing the critical energy fluence values from the literature with our measured values, the limits of initiation ability of the tested industrial detonators can be clearly seen. The PDV is to be recommended as a tool for research as well as for manufacturing quality control of detonators.

The proposed setup may also be used to characterize detonation wave parameters of new explosives prepared in miniature quantities provided the exact size of the shell and density of the explosive are known. In that case it would be possible to use the bottom free surface velocity to determine the detonation pressure of the explosive.

Acknowledgments

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