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Analysis of a self-centring detonation wave generator
Badanie generatora samocentrującej się fali detonacyjnej

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Abstract: *The aim of the study was to determine the parameters of a detonator generating a self-centring detonation wave, based on experimental and theoretical analysis. The methods for manufacturing self-centring detonation wave generators available in literature were reviewed and a detonator comprised of two explosives was proposed. The detonator geometry was analysed for its ability to centre the detonation wave. A physical detonator model was created and the detonation wave front downstream of the detonator, analysed and the detonator's capability to compensate an off-centre detonation initiation, evaluated. The wave fronts were recorded using pulsed x-ray radiography. The study showed that the proposed detonator provides a symmetrical initiation of the main charge for the initiation point (location) offset, lower than the assumed maximum offset.*

Streszczenie: *Celem pracy był dobór na drodze eksperymentalno-teoretycznej parametrów detonatora do generowania samocentrującej się fali detonacyjnej. Dokonano literaturowego przeglądu sposobów wytwarzania generatorów samocentrującej się fali detonacyjnej i zaproponowano detonator składający się z dwóch materiałów wybuchowych. Dokonano analizy geometrii takiego detonatora pod kątem możliwości centrowania się fali detonacyjnej. Zbudowano model fizyczny detonatora i zbadano kształt frontu fali detonacyjnej po wyjściu z detonatora oraz oceniono zdolność detonatora do kompensowania niecentralnego zainicjowania detonacji. Do rejestracji frontów falowych wykorzystano zestaw do rentgenografii impulsowej. Wykazano, że zaproponowany detonator jest w stanie zapewnić symetryczność pobudzenia ładunku głównego dla przesunięcia punktu (miejsca) zainicjowania detonacji mniejszego od założonego przesunięcia maksymalnego.*

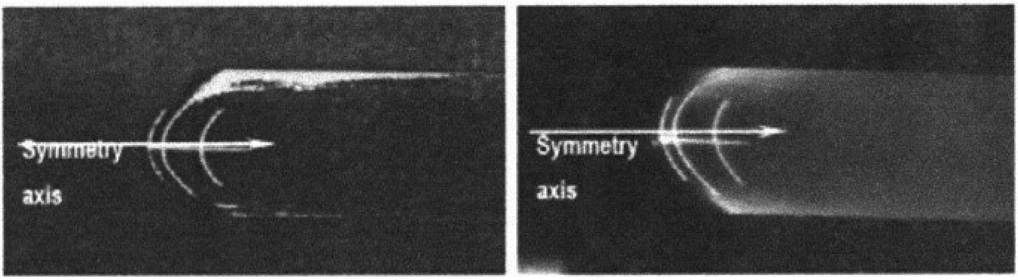
Keywords: *explosives, detonation, self-centring detonation wave generator, hollow charges*
Słowa kluczowe: *materiały wybuchowe, detonacja, generator samocentrującej się fali detonacyjnej, ładunki kumulacyjne*

1. Introduction

Literature related to the analysis of hollow charges using special booster initiation, also referred to as primary initiation, is not widely available. This is due to its intermediate effect on the interaction of the hollow charges minor. The main charge is initiated at the contact surface with the booster. The secondary initiation also affects the profile and further propagation of the detonation wave along the charge, as well as the efficiency of the hollow charge.

As a rule, detonation of the explosive in the hollow charge is initiated by a special system, referred to as the initiating/detonating system. Its chief component is the fuse initiating the detonation process in the booster charge. A typical fuse is cylindrical and relatively small (4 to 8 mm in diameter). It generates an initiation point and a more or less asymmetric detonation of the booster, which may affect the effectiveness of the hollow charge and its penetration capabilities.

The relationship between the axial symmetry of the detonation wave and the offset of the initiation point from the axis of symmetry was studied in [1-3]. Figure 1 shows streak camera images of the detonation wave front of a 40 mm diameter charge initiated with a 7 mm diameter fuse on the axis of charge symmetry (Figure 1a) and at a point offset from the axis by 4 mm (Figure 1b) [2]. The fuse offset shows clear asymmetry of the detonation wave front.



a) b)

Figure 1. Streak camera images of the detonation wave: a) initiation on the axis of symmetry, b) initiation with a 4 mm offset [2]

Figure 2 shows a schematic of the explosive system (booster) proposed for the generation of a self-centring detonation wave [1, 2]. The system includes two explosive charges of suitable shape and different detonation velocities.

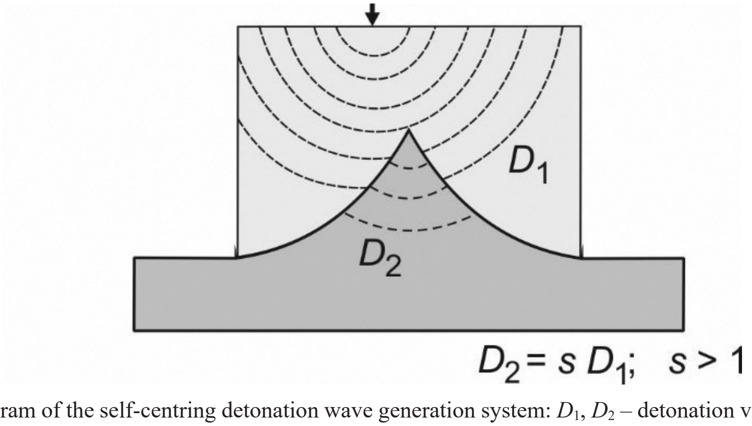
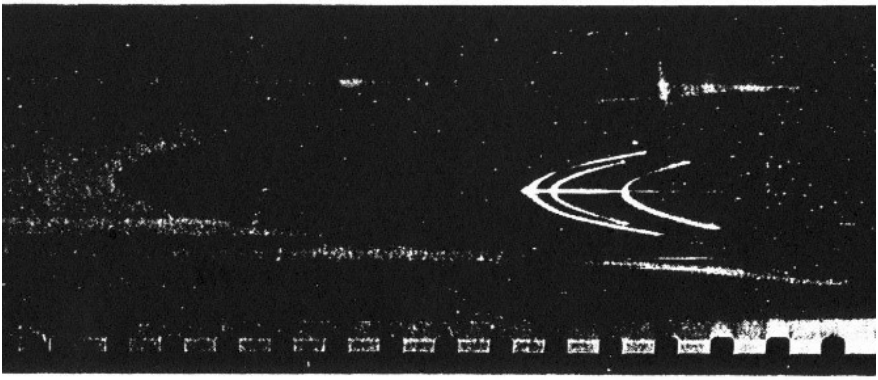


Figure 2. Diagram of the self-centring detonation wave generation system: D_1, D_2 – detonation velocity, $D_2 > D_1$

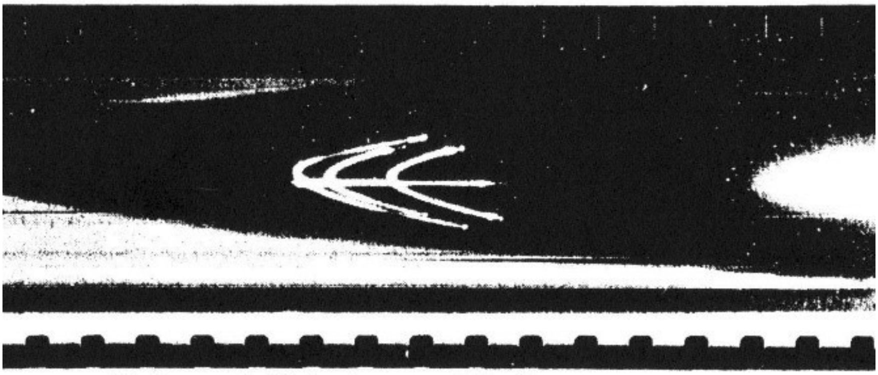
The detonation process and subsequent axially symmetrical detonation of the entire charge can be initiated when specific conditions are met [2]. Firstly, the shape of the contact surface between the top and the bottom charge, which may be the hollow charge itself, must ensure that the wave with velocity D_2 reaches the subsequent points at the contact surface before the wave with velocity D_1. Secondly, D_2 must be approx. 20% higher than D_1.

By selecting a suitable shape for the contact surface and the detonation velocity in both charges, the axially symmetrical detonation wave can be initiated despite the off-axis position of the fuse. Figure 3 shows steak camera images of the detonation wave front of a charge in accordance with Figure 2 after initiation with a 2.8

and 13.3 mm offset from the axis of symmetry [1]. In the first case, the detonation wave generated by the charge is almost symmetrical, whereas, in the second case, the initiation system was not able to compensate for the asymmetry of the wave front.



2.5 mm initiated eccentrically



13.5 mm initiated eccentrically

Figure 3. Streak camera images of the detonation wave in a self-centring initiating system after initiation at a 2.8 and 13.3 mm offset from the axis of symmetry [1]

As part of the study, an attempt was made to determine the parameters of an explosive system required to generate a self-centring detonation wave, using experimental and theoretical means. The geometry of the detonator was analysed to ensure that the wave front was symmetrical to the chosen offset initiation point. The results of the theoretical studies were used to create a physical model of the detonator, and its effectiveness was verified using pulsed x-ray radiography.

2. Analysis of the geometry of self-centring detonation wave generator

Assuming a stationary detonation process from its initiation, as well as point initiation of the explosive, the detonation image of the charge comprising two explosives with velocity D_1 and D_2 on the *x*-plane (radial coordinate of the cylindrical charge) and the *y*-plane (axial coordinate of the cylindrical charge) can be obtained using the method shown in Figure 4. It is assumed that in the *x-y* cross-section, the detonation waves are circular with the centre at the detonation initiation point (*b*, 0). The explosive with detonation velocity D_2 is initiated at point (0, *a*), after the wave with velocity D_1 reaches it. The curve separating the charges is a set of points which the detonation waves initiated at (*b*, 0) and (0, *a*) reach at the same time.

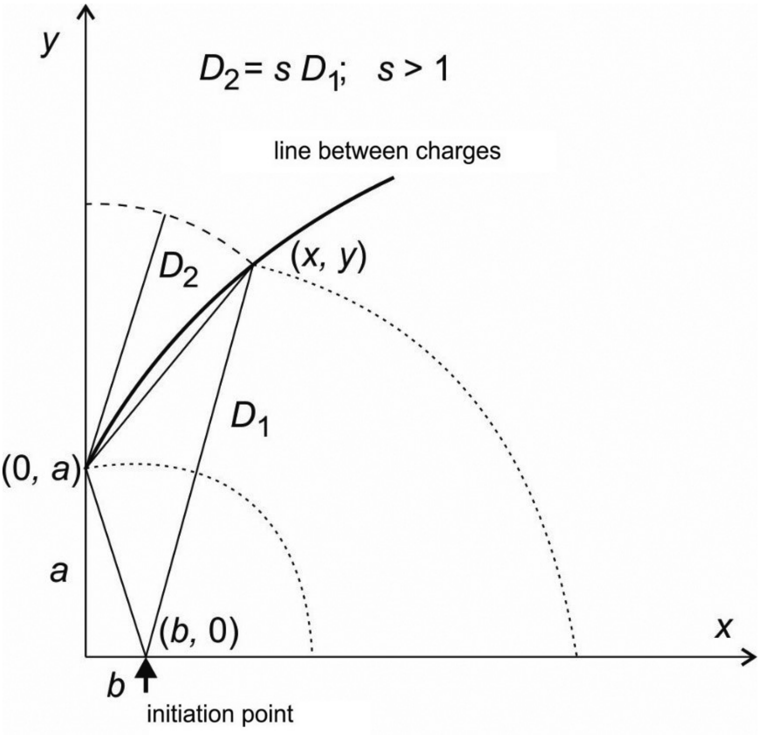


Figure 4. Wave front configuration in *x-y* axis

To determine the curve separating the charges, reached by both waves at the same time, the time point (*x*, *y*) reached by the waves on the curve, is calculated.
Time for the wave with velocity D_1 to reach point (0, *a*):

$$t_0 = \frac{\sqrt{b^2+a^2}}{D_1} \tag{1}$$

Time for the wave with velocity D_1 to reach point (*x, y*):

$$t_1 = \frac{\sqrt{(x-b)^2+y^2}}{D_1} \tag{2}$$

Time for the wave with velocity D_2 to travel from point (*x, y*) to point (0, *a*):

$$t_2 = \frac{\sqrt{x^2+(y-a)^2}}{D_2} \tag{3}$$

For the detonation wave with velocity D_2 to reach point (x, y) before the wave with velocity D_1 (which guarantees a symmetrical detonation wave front for the explosive with velocity D_2), the following inequality must be met:

$$t_1 > t_0 + t_2 \tag{4}$$

The position of the curve for which the condition $t_1 = t_0 + t_2$ is met, can now be determined i.e.:

$$\sqrt{(x-b)^2 + y^2} = \sqrt{b^2 + a^2} + \frac{1}{s}\sqrt{x^2 + (y-a)^2} \tag{5}$$

where $s = D_2/D_1$.
For each point above the curve (Equation 5), Equation 4 is met.
To determine the curve, the following numerical non-linear equation was solved for each x value:

$$F(y) = \sqrt{(x-b)^2 + y^2} - \sqrt{b^2 + a^2} - \frac{1}{s}\sqrt{x^2 + (y-a)^2} = 0 \tag{6}$$

Figures 5-10 shows sample calculation results for b = 2 and 5 mm and for a = 5, 10 and 15 mm.

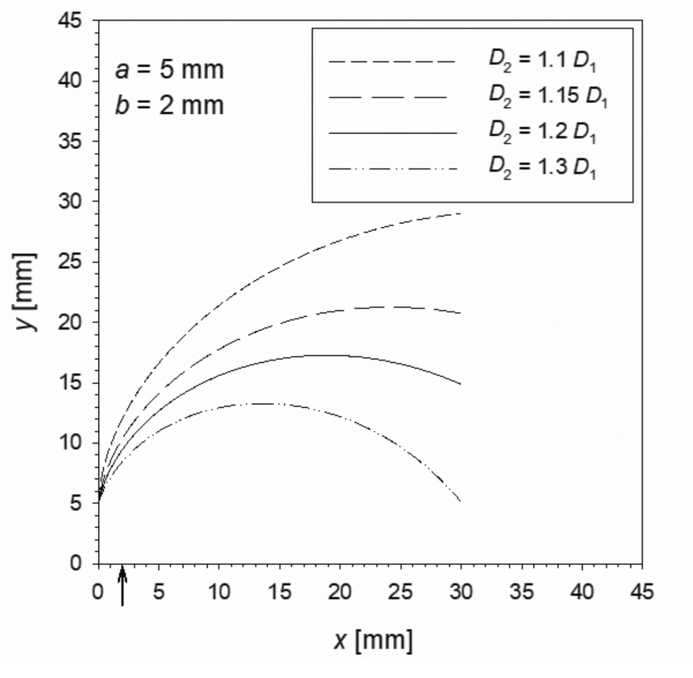


Figure 5. Profiles of an interface separating the charges for a = 5 mm and b = 2 mm (*arrow shows the initiation point*)

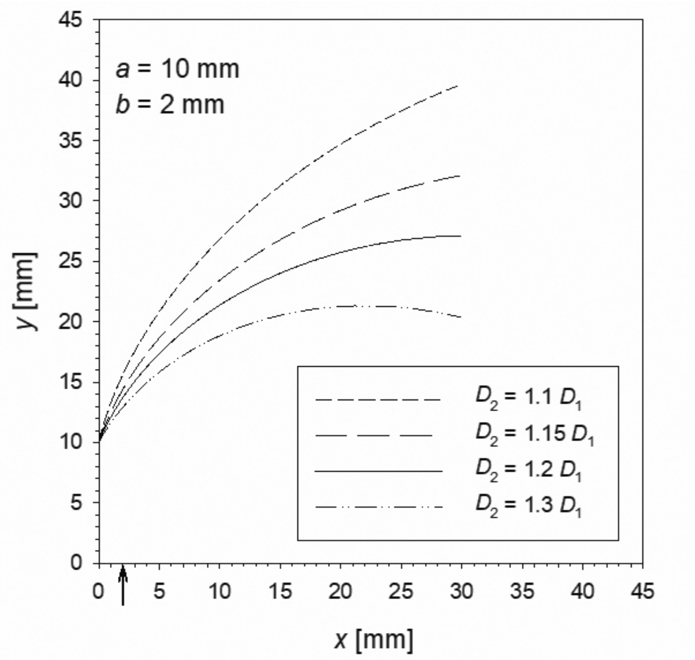


Figure 6. Profiles of an interface separating the charges for *a* = 10 mm and *b* = 2 mm

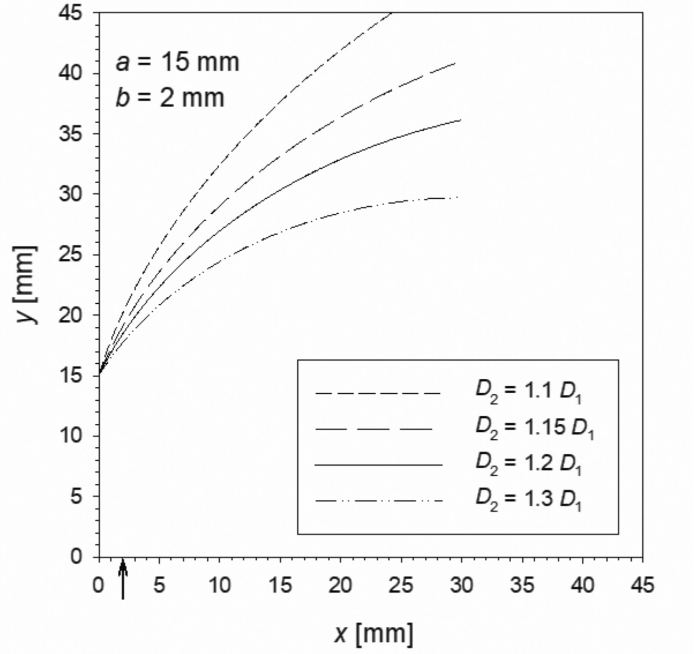


Figure 7. Profiles of an interface separating the charges for *a* = 15 mm and *b* = 2 mm

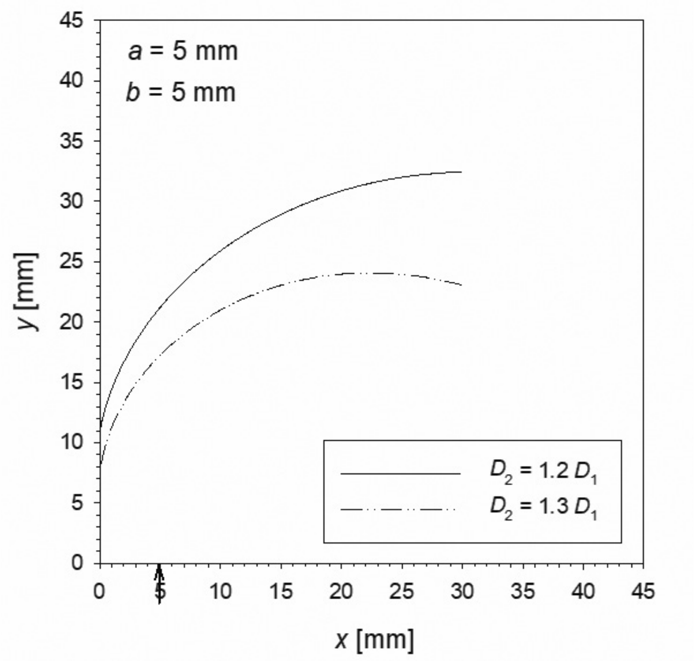


Figure 8. Profiles of an interface separating the charges for *a* = 5 mm and *b* = 5 mm

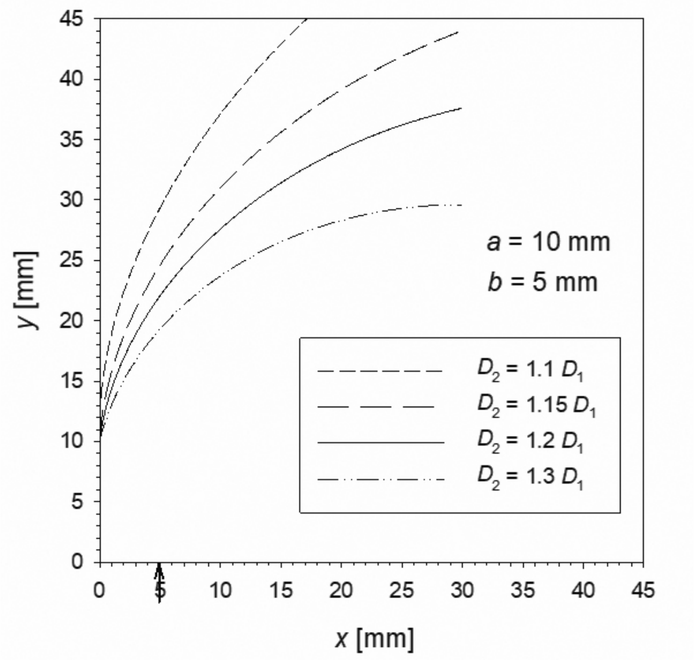


Figure 9. Profiles of an interface separating the charges for *a* = 10 mm and *b* = 5 mm

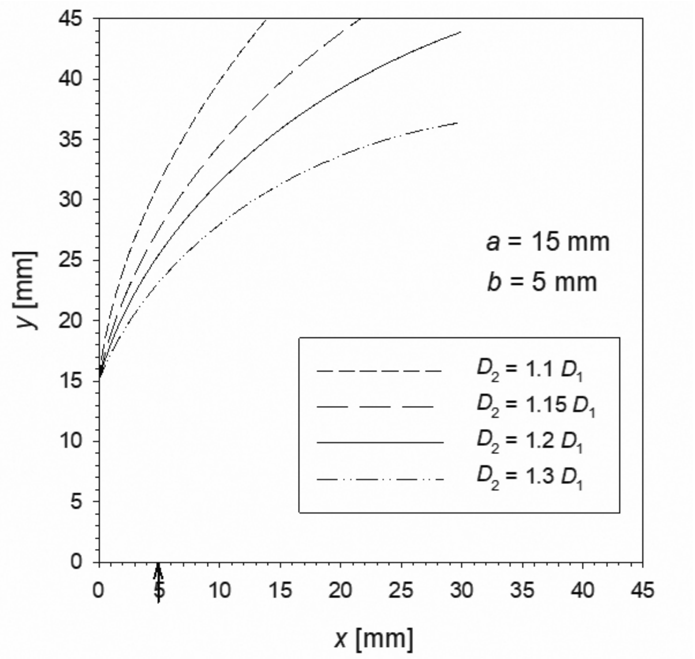


Figure 10. Profiles of an interface separating the charges for $a = 15$ mm and $b = 5$ mm

With an increase in parameter s, i.e. the ratio of velocity D_2 to velocity D_1, the radius of curvature of the interface between the explosives decreases for all studied cases of a and b. This means that by selecting the charge profile for a specified s_1, for all $s > s_1$, the detonation wave with velocity D_2 will reach the point faster than the wave with velocity D_1 and the initiation system will have served its purpose.

For a given b value (initiation point offset from the axis of symmetry) and s value, with an increase in distance between the beginning of the interface and the surface of the charge with lower velocity D_1, the angle between the curves and y-axis increases. For a given a value, the offset of the initiation point by a higher b value will reduce the angle between the curves and y-axis.

3. Physical model of the self-centring detonation wave generator

To determine the curvature of the surface separating two charges of the self-centring detonation wave generator, it can be assumed that the ratio between the detonation velocity $s = D_2/D_1$ in the generator will be higher than 1.2, and the thickness of the explosive layer with lower velocity over the cone of the second explosive (a in Figure 4) will be over 10 mm. It can also be assumed that the diameter of the top section of the charge (Figure 2) will be 30 mm. A fuse with a maximum diameter of 6 mm will be used to initiate the top charge, thus, the maximum deviation of the initiation point will not exceed 3 mm.

Figure 11 shows the curve corresponding to the contact surface between the different explosive charges for $s = 1.2$, $a = 10$ mm, $b = 3$ mm. The red line shows the curve approximating a section of the circle with a radius r and a range x from 0 to 15 mm.

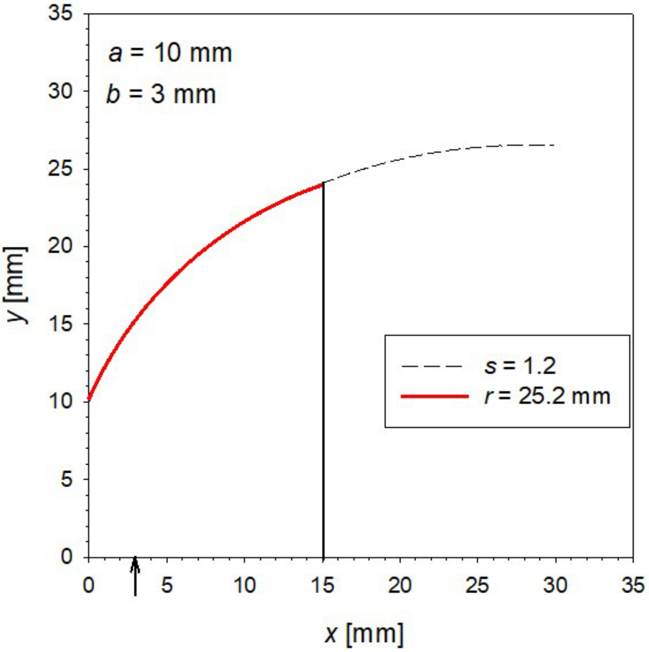


Figure 11. Profile of the surface separating the charges in the self-centring detonation wave generator: $a = 10$ mm, $b = 3$ mm and $s = 1.2$ and approximating section of the profile using a section of the circle with a radius $r = 25.2$ mm

Figure 12 shows the shape of the self-centring detonation wave generator. The top charge was made of pressed TNT with a density of 1.59 g/cm^3 and a detonation velocity D_1 = 6860 m/s. The bottom charge of the generator was made of pressed DPX-4 (octogen/Viton 90/10) with a density of 1.82 g/cm^3 and a detonation velocity D_2 = 8515 m/s) The ratio between the detonation velocities of the materials is 1.24, and is higher than the value of $s = 1.2$ used at the design stage. Figure 13 shows the shape of the die used for pressing the self-centring detonation wave generators.

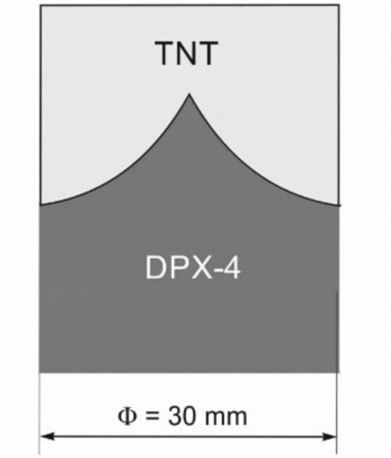


Figure 12. Detonator (self-centring detonation wave generator) diagram

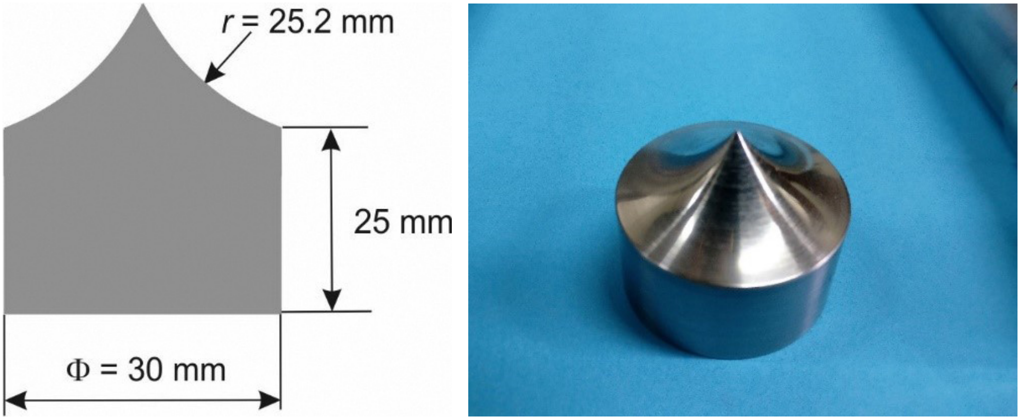


Figure 13. The shape and image of a die used for pressing the top part of the self-centring detonation wave generator

After pressing the charge containing material with the lower detonation velocity (TNT), it was placed in a 30 mm diameter die, covered with the required amount of explosive with the higher detonation velocity (DPX-4) and pressed again. The effect of the initiation point on the symmetry of the detonation wave in the main charge (pressed DPX-4 explosive) was tested using the test setup shown in Figures 14 and 15. The initiator was a metal ring containing a 0.9 g of pressed phlegmatized hexogen (RDXph) (Figure 16). The initiator was placed in the centring ring with its axis of symmetry offset by 0, 2, 4 or 6 mm from the axis of the detonator (Figure 17).

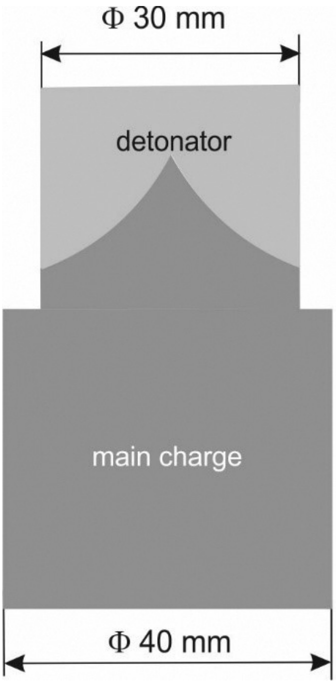


Figure 14. Test setup used to determine the effect of off-centre detonator initiation on the shape of the detonation wave in the main charge

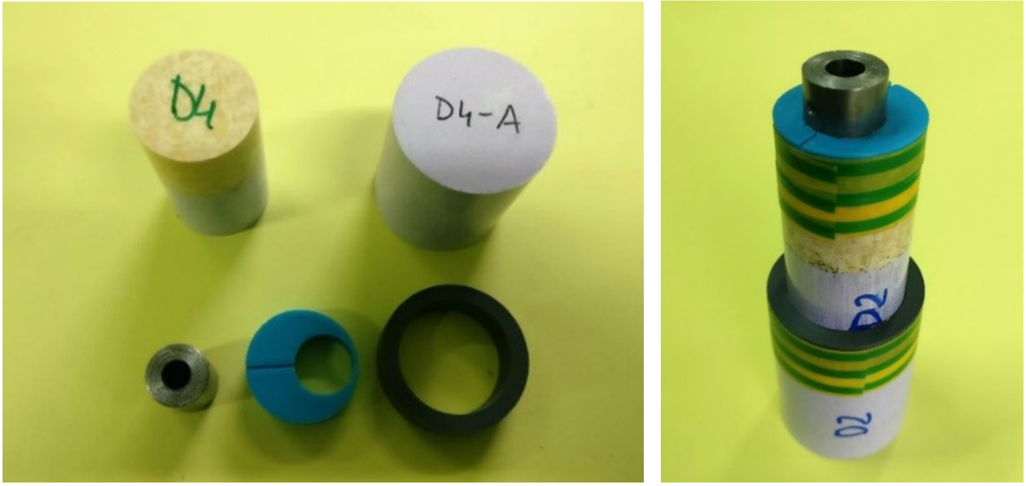


Figure 15. Test setup for the self-centring detonation wave generator testing

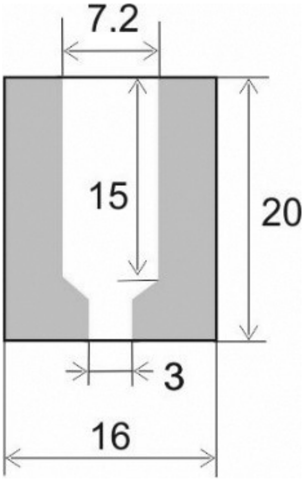


Figure 16. Initiating system

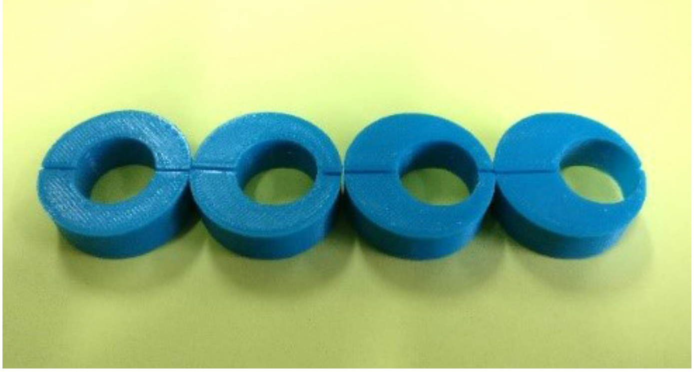


Figure 17. Centring discs for aligning the initiator

4. Test results

The shape of the detonation wave front in the main charge with the self-centring wave generator was analysed using SCANDIFLASH X-ray set, successfully applied to record the detonation wave and shockwave fronts [4, 5]. Figure 18 shows the x-ray images of four test setups used in the analysis of detonator effectiveness. The x-ray images were taken at $t = 9$ µs from detonation initiation. Figure 19 shows the measured results. Figure 20 shows the photographs and the wave fronts.

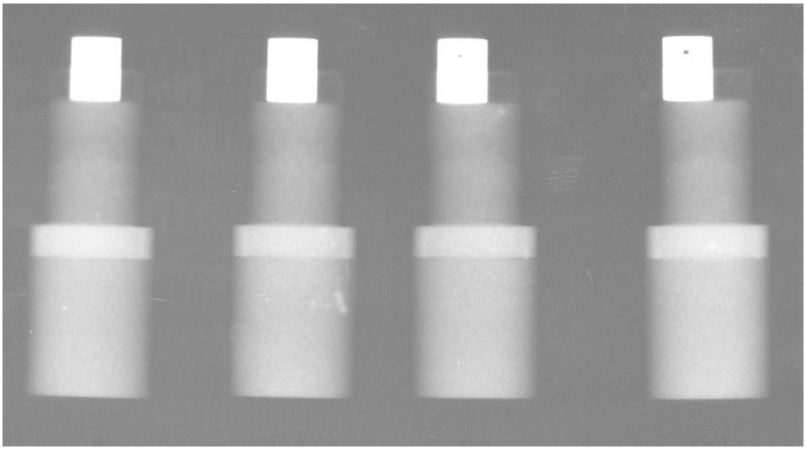
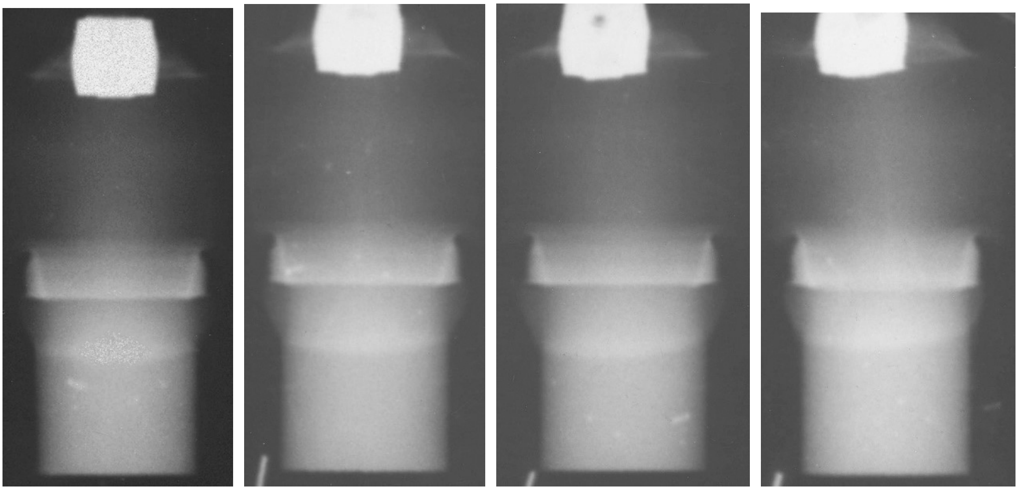
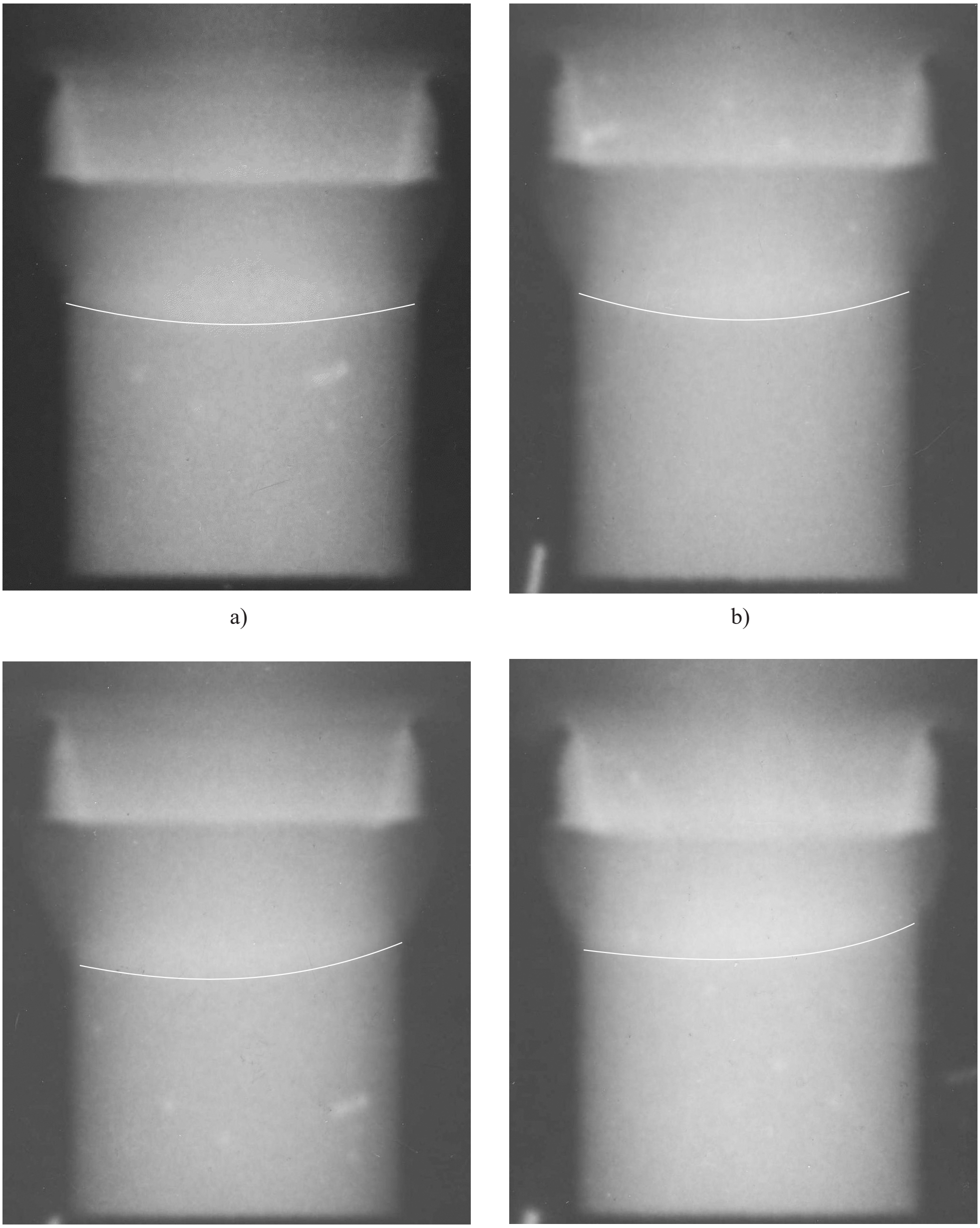


Figure 18. X-ray images of the test setups with self-centring detonation wave generator



a) b) c) d)

Figure 19. X-ray images of wave fronts in the test setups with self-centring detonator (initiation point offset by 0, 2, 4 or 6 mm – images from a) to d), respectively)



a) b)

c) d)

Figure 20. X-ray images of wave fronts for the initiation points offset by 0, 2, 4 or 6 mm – images from a) to d), respectively

Thorough analysis of the shape of the detonation wave showed that for the initiation in the central point or in the point offset by 2 mm, the wave front of the main charge is symmetrical. For higher offsets of the initiation point, the wave front is asymmetrical. At the detonator design stage it was assumed that the detonator would be capable of generating a symmetrical wave for initiation point offsets up to 3 mm. The experimental results are consistent with the assumption.

The designed detonator diameter is 30 mm as is its minimum height. The dimensions can be reduced slightly for use in large hollow charges. Using this type of detonator in medium-calibre ammunition (40 mm) is difficult due to the small size of the hollow charge.

5. Conclusions

- Based on the review of the available literature on the methods for producing self-centring detonation wave generators, a detonator comprising two explosives with different detonation velocities was proposed. The detonator's geometry was analysed and the shape of the contact surface between the two explosives ensuring its effectiveness was determined. The results showed that the shape depends on the ratio between the detonation velocity of the explosives used, the thickness of the explosive layer above the beginning of the curve on the axis of symmetry and the maximum initiation point offset assumed.
- A physical detonator model was built. Two materials of different detonation velocity were used (phlegmatized octogen DPX-4 and TNT with a detonation velocity of 8515 and 6860 m/s, respectively). Dies were designed in which the detonator and main charge components were pressed. The wave fronts were recorded using pulsed x-ray radiography. The effect of change in the initiation point offset in the generator on the shape of the detonation wave front in the main charge, was analysed. Based on the results, the detonator's capabilities of compensating for an off-centre initiation point, were estimated. The results show that the detonator is capable of compensating the initiation point offset within the range assumed at the design stage, i.e. 3 mm. Using this type of detonator in medium-calibre ammunition (30 mm) is difficult due to the small size of the hollow charge these use. However, this type of detonator can be used in large-calibre ammunition (120 mm).

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References

[1] Held M. Streak Technique as a Diagnostic Method in Detonics. *Proc. 1st Int. Symp. Ballistics*, Orlando, FL, **1974**, IV/177-210.

[2] Ugreic M., Blagojevic M. Initiation and Correction of the Detonation Wave in the Shaped Charge Peripheral Zone. *Sci. Tech. Rev.* **2011**, *61*(1): 17-24.

[3] Chou P.C., Flis W.J. Recent Developments in Shaped Charge Technology. *Propellants Explos. Pyrotech.* **1986**, *11*(3): 99-114.

[4] Trzciński W.A., Cudziło S., Szymańczyk L. Determination of the Detonation Pressure from a Water Test. *Eng. Trans.* **2015**, *49*(4): 443-458.

[5] Trzciński W.A., Barcz K. Investigation of Blast Wave Characteristics for Layered Thermobaric Charges. *Shock Waves* **2012**, *22*(2): 119-127.

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