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Influence of Explosive Composition and Structure on Shock to Detonation Transition

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This paper includes the results of the examination of the explosive detonation process development by shock wave initiation. A new method, a modified GAP test, has first been defined for examining the explosive sensitivity to shock waves. The GAP system consists of a flat shock wave generator and an attenuator of polyethylene with a determined shock adiabate. Shock sensitivity is examined for FH-5 and FP-5 explosive charges and for LKE-11 and LKE-15 cast composite explosives using the modified GAP test. The shock to detonation transition (SDT) process was tested in cast composite (LKE-70/10, LKE-11 and LKE-15) and pressed explosives (FH-5 and FP-5) for different values of the shock wave pressure. The distance to detonation and the "Pop-plot" diagram were determined for each explosive composition and shock pressure intensity after the analysis of the obtained results.

Key words: **shock wave, detonation initiation, mass velocity, cast explosive, pressed explosive, Lagrange velocity gage, GAP test.**

Introduction

THE most common way of initiation of detonation in complex weapons is initiation of detonation by a shock wave. Detonation area investigation is often carried out on systems with this type of initiation. The initiation of explosive by a shock wave is a non-stationary process of a mutual action of the shock wave and the non-decomposed explosive in which the shock wave causes chemical decomposition. which is very interesting and complex for theoretical consideration.

The initiation of explosive by a shock wave was earlier investigated in the Military Technology Institute (VTI) by the GAP test, in which the shock wave pressure was determined, and by the detonation process development and flow with registering a particle velocity change through an explosive charge until steady detonation was achieved. In one explosive sample, only one gage was embedded, and flow data were collected through the results of more experiments. Therefore, the detonation development was comprehensively monitored by using the Lagrange particle velocity gage technique. The electromagnetic gage package was developed and its functionality was examined. It was embedded in cast composite explosive under the angle of 30^{o} with regard to the front surface of the explosive charge.

Shock initiation of explosives

Explosive materials are compact sources of chemical energy, designed to decompose very rapidly if sufficient energy has first been added to get the process started – it is the initiation or ignition of explosives. Explosives can be initiated in many ways: by heat, electrostatic impulses, friction, shock waves, light pulse, laser ray, or any combination of these energy sources.

This work concentrates on the study of the shock initiation mechanism, i.e., the explosive sensitivity initiated by a shock wave of a determined intensity. To help understanding the initiation and sensitivity of explosive materials subjected to shock waves, a variety of experimental tests is routinely conducted. Although the experiments give valuable information on the sensitivity of shock initiated explosives, many of the testing methods provide little insight into the fundamental physical and chemical processes occurring during an initiation event.

When discussing the shock initiation of explosives, the physical nature of the explosive has to be known. The explosive materials themselves are commonly referred to as homogeneous or heterogeneous explosives. Homogeneous explosive (liquids or single crystals) initiation occurs by a thermal explosion. Explosive compounds are heterogeneous systems, containing explosive crystals and a binder component with some porosity (void or gas cavities), so there is a clear limit between different constituents.

The key to understanding initiation in heterogeneous explosives was first discussed in detail by Bowden and Yoffe [1]; they introduced the concept of the "hot-spot" or ignition sites. They adopted a thesis that explosive un-homogeneity leads to discontinuity of mechanical and thermal energy distribution behind the shock wave front, which gives a specific, multidimensional character of the process. Local regions of high energy density, hot spots, are formed in the explosive charge as a response to the shock. Hot spots are small localised regions of elevated temperature that are produced by the interaction of a shock

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wave with the inhomogeneities in a heterogeneous explosive in which the initiation and decomposition reaction can occur.

Based on the experiment, the shock initiation process in heterogeneous explosives is usually described as having two separate phases: 1) an ignition phase where hot spots are created due to shock compression, and the subsequent chemical decomposition of the explosive in these localized heated regions, and 2) a growth phase where the build-up of chemical reaction occurs as the hot spots grow and coalesce to consume the remainder of the explosive material.

It has been noted that the ignition of hot spots does not necessarily result in a buld-up of the detonation process. Hot spots are cooled by the conduction of heat from the hot spots into the cooler material surrounding them. If hot spots are hot enough for the material to begin to react before heat conduction cools it too much, the surrounding material can initiate and the reaction can then grow to detonation. This process is known as the shock-to-detonation transition (SDT) process. In it, hot spots decompose and add their energy to the flow. This strengthens the leading shock so that when it interacts with additional heterogeneities, higher temperature hot spots are formed and more of the explosive is decomposed. The shock wave grows stronger and stronger, releasing more and more energy, until it becomes strong enough to produce a self-sustaining propagating detonation.

Bowden and Yoffe [1] have noticed that there are many proofs for the claim that the explosive initiation is thermal in its origin; mechanical energy can be converted into heat and concentrated in small volumes, hot spots. Hot spots are small, but big enough compared with molecule dimensions. The authors have shown that there are three basic methods of hot spot formation: adiabatic compression of trapped gas spaces, friction between sliding or impacting surfaces (or between explosive crystals and/or grit particles in an explosive - impurities, among explosive particles, i.e., in explosive crystals), and viscous heating of the material rapidly extruded between impacting surfaces.

Many other mechanisms of hot spots formation were introduced and discussed by authors like Field [2], Mader [3, 4], Campbell [5] and others [6 - 9].

Typical dimensions of hot spots are 0.1 - 10 μm, and temperatures are higher than 700 K [1].

The explosive sensitivity depends on the nature, the concentration and the distribution of hot spots in the explosive charge. The explosive initiation of detonation is caused by some minimum energy value. Therefore, the most convenient is to choose a critical energy value, a reaction threshold, as a criterion for explosive initiation. This value is expressed in many ways. The condition for the shock wave pressure to be higher than some critical value is completed by the duration of its action on the shock wave front - it is so-called “critical energy”, defined as:

$$P^2\,\tau = const,\ \frac{P^2\,\tau}{\rho_0\,U} = const,\ u^2 = const...$$

The critical energy concept in connection with shock waves of short duration is introduced in [10] - the critical energy depends on the amplitude of shock wave pressure and its duration, and it is a constant for certain explosive compounds. The initiation will cause detonation if the shock wave parameters are higher than the critical value.

The explosive decomposition reaction in hot spots begins just after the shock wave front through a two-step process: “ignition and growth” of the reaction. The initiation process goes on over so-called pore collapse and the viscoplastic heating of the explosive material around the pores. A few tens of nanoseconds after the front wave effect, the reaction of material decomposition begins at the boundary with the pores; the cavity is full of hot reaction products and a hot spot is formed.

Shock initiation processes can be investigated by using gages embedded in explosive charges, which follow the development of the reaction wave in a function of time. The registered records of gages represent valuable information about the homogeneous/heterogeneous nature of the reactive process development; they are also significant for the initiation process simulation with a reaction flow model. Investigators used electromagnetic and pressure gages to examine the SDT process. Incorporation of more gages in a few positions in the same explosive sample enables registering the process parameters (mass velocity or shock wave pressure) from the shock conditions to the detonation. These gages are so-called Lagrangian because they move with the material in which they are embedded. Measuring in a few Lagrangian positions in one experiment gives the information about the flow rate, based on the Lagrange analysis.

A special type of electromagnetic gages, a membrane, was used for the first time in [11]. The gage is a membrane consisting of 25 μm thick FEP Teflon layer with a layer of 5 μm of aluminium glued to it. It is then coated, exposed and etched with the desired pattern. Then another layer of 25 μm thick FEP Teflon is glued on top. A completed membrane is about 60 μm thick. These gages are made by RdF Corp. of Hudson, NH.

Experimental results and analysis

Modified GAP Test

The system used for the shock sensitivity of explosive determination, the GAP Test, is based on the critical pressure determination for which the limited deformation of the metal cylinder is obtained. In this paper, a modified GAP Test is used with the plane wave generator, PWG, instead of the booster [12]. The change was necessary because of the electromagnetic Lagrange gage used during the SDT investigation. It is well known that the basic condition for the Lagrange analysis is the existence of the one-dimensional shock wave – this condition is provided by the PWG. Therefore, the modified GAP Test (the GAP system is 50 mm in diameter) consists of [13]:

1. PWG – active explosive charge;
2. An attenuator of polyethylene PE 1000 with the known shock Hugoniot adiabate [14]. The adiabate was determined by measuring the shock wave and mass velocities through PE1000:

$$P_{cr} = 165.467 \cdot e^{-0.0376 \cdot d}\ \text{(kbar)}, \qquad (1)$$

where P_{cr} is the critical pressure of initiation (kbar) and d is the thickness of the attenuator (mm). By this expression, the shock wave pressure intensity can be obtained for the attenuator thickness of interest.

The impulse pressure length is about 2 and 2.5 μs.

3. The tested explosive charge whose thickness is equal to the diameter;
4. Copper or aluminum cylinder (thickness is equal to the diameter); the deformation of the metal cylinder exposed to the shock wave effect is used to estimate critical initiation conditions.

The result - Cu/Al cylinder deformation - is shown in Fig.1.

Figure 1. Deformation of copper cylinders exposed to different intensities of shock wave effects (the boundary deformation is marked)

The shock sensitivity of two cast composite explosives, LKE-11 (HMX/AP/Al/HTPB 40/20/25/15) and LKE-15 (HMX/AP/Al/HTPB 33/20/32/15), was determined by using the modified GAP Test; the critical pressure value for LKE-11 was 21.47 kbar and 22.55 kbar for LKE-15. In addition, the shock sensitivity of the pressed FH-5 and FP-5 was determined. The critical pressures were: P_{cr} = 11.33 kbar for FH-5 and 6.83 kbar for FP-5.

Electromagnetic method with a pulse magnetic field

Signals from the electromagnetic gage package are registered by using the electromagnetic method with a pulse magnetic field. The basic elements of the measuring system, carried out in the VTI, are as follows [15]:

- A high voltage device with Helmholtz coils – Helmholtz coils consist of two identical rings made of nonmagnetic material, placed parallelly at a distance equal to the ring diameter; the rings have gutters along the outside edge with the coils of copper wire. The pulse, high voltage device generates high-intensity magnetic fields. It consists of a battery of condensers and electrical circuits for steering, supplying, firing and discharge. The pulse magnetic field is semi-sine with a duration of 3.2 ms; an intensity of the magnetic induction B is up to 134 mT. *B* (*U*) dependence is linear;
- The electromagnetic gage – it is a thin copper or aluminum foil in a "rectangular loop" shape. The gage package and Al foil, of 0.100 mm thickness, are used for the SDT investigation;
- A system for the initiation of an explosive sample and 3-channel delay generator – these elements of the system have to initiate the explosion in an interval of time in which the intensity of the magnetic field is maximal. The plane wave generator, a part of the initiation system, ensures a parallel detonation front access to the active element of the gage. An igniter has the induction time of 5±0.3 μs;
- A digital oscilloscope with coax-cables – a bandwidth of the registering system has to be over 100 – 500 MHz (time resolution min 10 ns).

For the experimental examination of SDT, the electromagnetic gage package was constructed in the VTI, based on more paper data. It is shown in Fig.2. The characteristics of the package are shown in Table 1.

Table 1. Electromagnetic gage package characteristics

Characteristic	Value (mm)
Cu foil thickness	0.01
active element length	10-30 (difference in lengths for 2 neighbouring gages - 5 mm)
active element thickness	2
distance between active elements	3
gage leads length	25
gage leads thickness	1
thickenss of cable leads	1

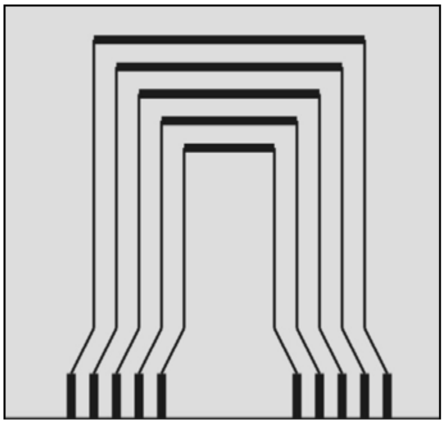


Figure 2. Electromagnetic gage package

SDT examination in cast composite explosives

The electromagnetic gage package was embedded in cast composite explosive; an explosive charge of 50 mm in diameter was machined so the inclined surface made a 30° angle with the front surface. The cutting surface was plain, convenient for the embedding of gages. The gage membrane was glued to the explosive sample with the gages carefully aligned to the sample reference line. Then the top piece was glued on (see Fig.3).

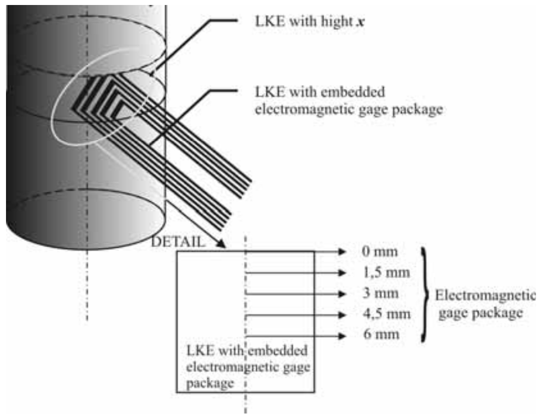


Figure 3. Experimental sample for the SDT investigation in cast composite explosive (*x* – boundary with the attenuator)

The mass velocities were measured in HMX/Al/HTPB 70/10/20, LKE-70/10 explosive, under shock wave pressure loading of P_{SW} = 25.53 kbar, slightly higher than the critical pressure; the gage membrane distance from the attenuator varied in the samples.

The shock wave development, based on gage records, can be presented two-dimensionally, in the u_m-t plane, Fig.4, or three-dimensionally, as in Fig.5. A mass velocity change per time and in connection with the distance *x* is shown in Fig.5 for a shock wave pressure value of 25.53 kbar. It can be concluded from Fig.4 that the mass velocity $u_m(t)$ has a wide and rounded peak (based on two first records), which indicates an absence of detonation. Next three records have a more expressive peak.

It can be noted that there is almost alternately a drop/growth of the shock wave intensity for *x* = 0 - 20 mm. The shock wave velocity follows the same trend: it grows and drops (for example, shock wave velocities for *x* = 18.5 mm and *x* = 20 mm, drops from 3850 m/s to 2630 m/s, followed by a simultaneous intensity growth for 27% and a drop for 25%). In a region for *x* from 29.5 mm to 35.5 mm, the appearance of the characteristic maximum can be noticed on the gage 4 record; it can be concluded that the detonation wave development starts at the distance of x^* = 34 mm. The same shape occurs on the gage 5 record, but with somehow lower intensity of wave pressure. The similar appearance has been noticed on other gage records – a lower amplitude is not in agreement with shock wave development, which transfers to detonation, but with a non-stationary flow, i.e. the presence of a reflected wave from the lateral side of the charge.

The detonation process development was examined under the initiation of LKE-70/10 by a shock wave intensity of around 1.5, 2 and 3 times higher than 25.53 kbar, i.e. of 38.04 kbar, 51 kbar and 76.55 kbar (electromagnetic gages were embedded at the distance x = 20.2 - 26.2 mm, 15 - 21 mm and 11.1 - 17.1 mm, respectively) to get the Pop-plot diagram, the distance to detonation x^* vs the shock wave pressure P_{SW}. The example of the obtained records $u(t)$ and a 3D view of the Lagrangian gages is shown in Fig.6.

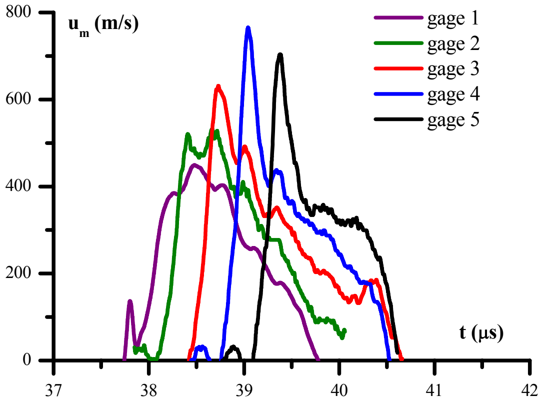


Figure 4. $u_m(t)$ based on the electromagnetic gage records (a gage package embedded in LKE-70/10: x = 29.5 - 35.5 mm)

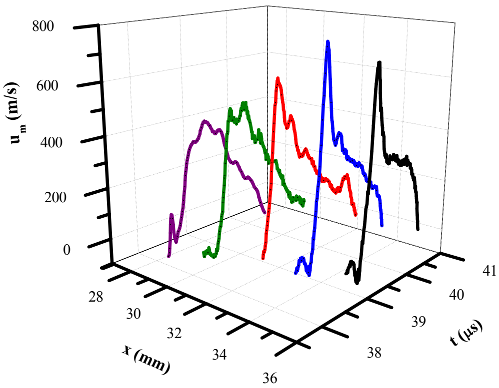
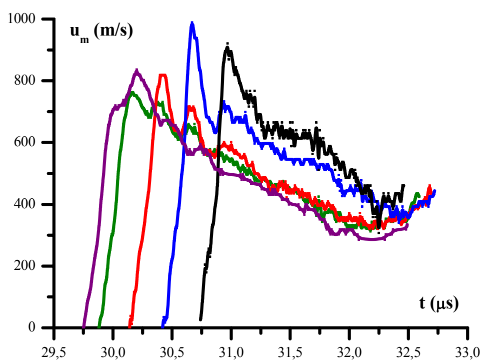


Figure 5. $u_m(t)$ in the function of the distance x in LKE-70/10 (x = 29.5 mm - 35.5 mm)



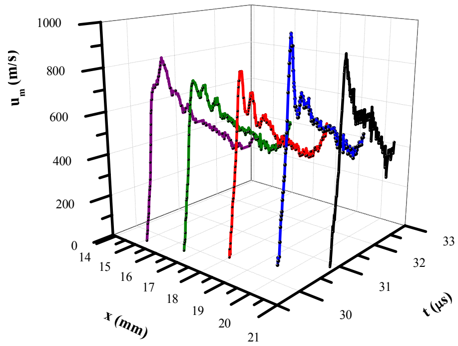


Figure 6. $u_m(t)$ and mass velocity development through LKE-70/10 obtained under the shock wave pressure intensity of 51 kbar

The distance to detonation values as a function of the initial shock pressure are shown in Table 2.

Table 2. LKE-70/10 - distance to detonation as a function of the initial shock pressure

P_{SW} (kbar)	x^* (mm)
25.53	34
38.04	24.7
51.00	19.5
76.55	14.1

The shock wave velocity trajectories, U, and the maximum values of mass velocities, $u_m(max)$, as a function of distance x are shown in Fig.7 for a shock pressure intensity of 25.53 kbar. It can be noticed that the maximum values increment is insignificant at the beginning and smaller than the shock wave velocity increase. Then, the change rate of the maximum values follows the change of the shock wave velocity; it is even somehow higher.

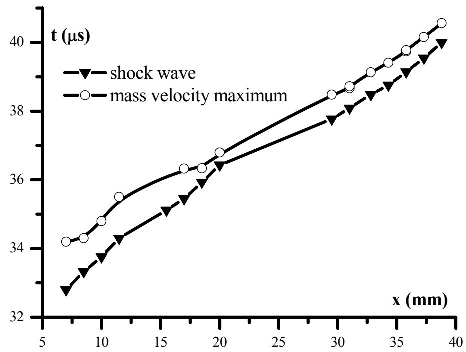


Figure 7. Trajectories of the shock wave velocity and the maximum values of mass velocities for LKE-70/10; PSW = 25.53 kbar

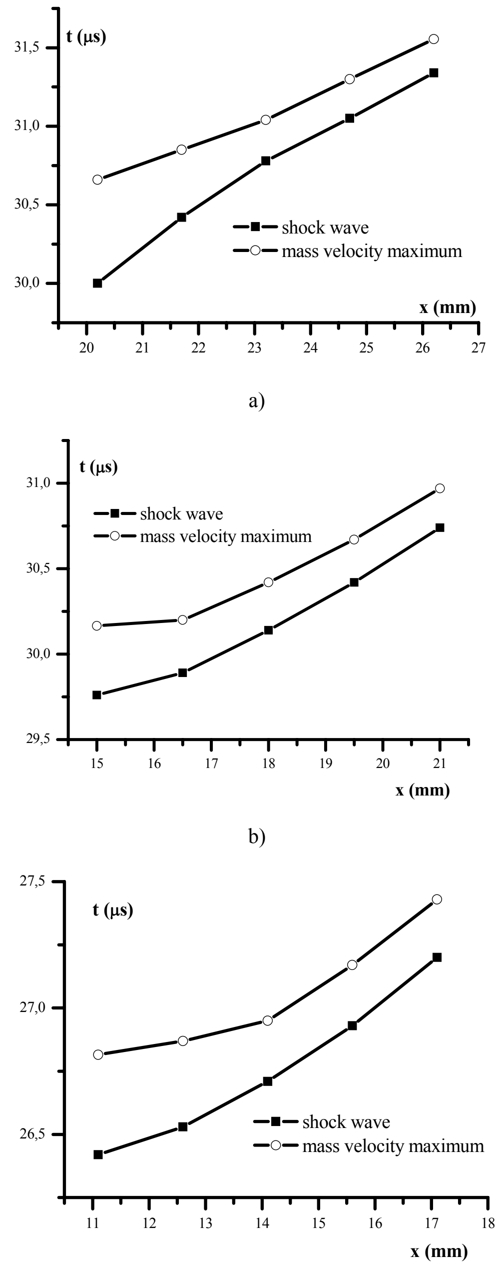
The processes in the growth to detonation for sustained shocks were divided into five stages in [16]:

- Stage I: a constant intensity shock with the particle velocity history initially constant; the particle velocity later develops and has a low wide domelike structure. The peak velocity $u_m(max)$ initially grows very slowly and then accelerates to a nearly linear growth rate. The velocity of the trajectory of the peak is much slower than the shock wave, i.e. the reaction dome is subsonic with respect to the shock wave,
- Stage II: a constant intensity shock with the particle velocity histories forming a broad, nearly constant width dome, but with a linearly growing peak. The trajectory of the peak is nearly parallel to the shock wave – the reaction dome remains subsonic with respect to the shock wave,

- Stage III: the shock intensity grows at first very slowly and then gradually more rapidly. The particle velocity histories grow nearly linearly in the amplitude but get narrower with the depth of explosive. The trajectory of the peak begins to accelerate and becomes supersonic with respect to the shock wave,
- Stage IV: the shock intensity grows rapidly; the peak has caught up with the shock wave so the particle velocity decreases behind the shock wave,
- Stage V: detonation with a von Neumann spike.

Stages I and II are represented to around 32.5 mm and the reaction is subsonic at the distance of $x < 32.5$ mm in the explosive charge with respect to the shock, as indicated in Figs.4 and 7. After 32.5 mm, the electromagnetic gage record contains a sharp peak and there is an acceleration of the peak trajectory; the reaction becomes supersonic.

The trajectories U and $u_m(max)$ for the shock wave pressures intensities 1.5, 2 and 3 times higher are shown in Fig.8.



a)

b)

c)

Figure 8. Trajectories U and $u_m(max)$ for LKE-70/10; P_{SW} = 38.04 kbar (a), 51 kbar (b) and 76.55 kbar (c)

There is initially a higher shock wave velocity increment with respect to $u_m(max)$ under pressure of the shock wave of 38.04 kbar in the examined region (x = 20.2 mm to 26.2 mm); for the other two values of $P_{SW,}$ the peak velocity is initially almost constant, or it increases slowly. Common for all three graphs is the parallelism of two trajectories from gage 3 of the gage package.

Stage IV was not noticed for any of pressure values because of the choice of the distance x, i.e., mass velocity decrease behind the shock wave front and the steady-state detonation with the von Neumann spike (stage V) were not registered, but SDT was.

Mass velocities were measured in five experimental samples exposed to a shock wave of 25.25 kbar in intensity, for LKE-11 (HMX/AP/Al/HTPB 40/20/25/15) cast composite explosive [17]; the gage package distance from the attenuator varied in the samples (it was 0 mm, 7 mm, 14 mm, 39.9 mm and 44 mm). These was completed with the regions x = 39.9 - 44.4 mm and 44 - 50 mm, Fig.9.

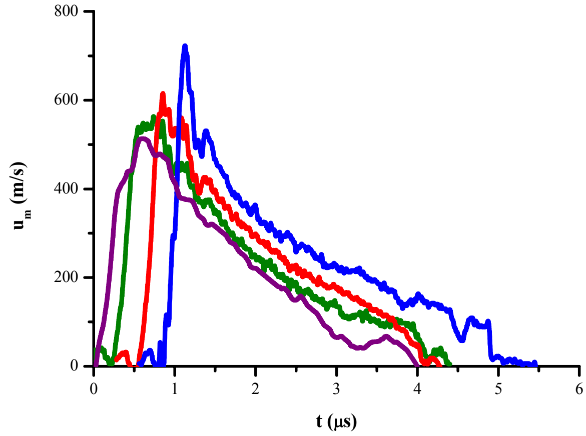


Figure 9. $u_m(t)$ for LKE-11 explosive charge (39.9 - 44.4 mm)

The non steady-state/stationary flow and an appearance of the detonation wave are characteristic for the examined region. It can be noticed that there is a characteristic triangular $u_m(t)$ profile for $x > 40$ mm [14] which indicates an appearance of a detonation wave. The detonation wave structure is clearly expressive: there is mass velocity increase immediately after the shock wave front and the von Neumman spike followed by the Taylor rarefaction wave. The amplitude of the wave increases with the increase of the distance that the shock wave front passes through the explosive charge; this is a rise at the wave front. In addition, peak velocity increases; this is a rise behind the shock wave front.

What is characteristic for the obtained mass velocity profiles is that they initially have a somehow rounded peak with the increasing amplitude, and then a peak width of the record narrows with the shock wave propagating. Close to and in detonation conditions, the gage records have the von Neumman spike structure. A triangular wave profile for gage position x = 44 mm, Fig.9, is an indication for the shock to detonation transition. Whether the detonation wave will develop to a steady-state detonation or the wave will extinquish depends on the explosive nature and the shock wave intensity. The shape of the electromagnetic gage record (increasing – peak value – decreasing) can be explained hydro-dynamically [18]. It is a result of the shock wave strength gradient which is, on the other hand, a result of the time dependence of energy liberation. The mass velocity will increase if the shock wave intensity behind the gage is higher than the intensity in front of the gage. Contrary, the mass velocity will decrease if the shock wave intensity in front of the gage is higher than the intensity behind the gage. This is noticed on the decreased part of the $u_m(t)$ record.

An additional examination was carried out for the region 44 - 50 mm to confirm the existence of detonation. There is the detonation wave developing for x^* = 44.4 mm, based on the registered mass velocity records, i.e. the distance to detonation is 44,4 mm for the shock wave pressure of 25.25 kbar.

The Pop-plot diagram for LKE-11 was obtained for the shock wave intensities of 37.89 kbar, 50.43 kbar and 75.69 kbar (1.5, 2 and 3 times higher than P_{SW} = 25.25 kbar). The Lagrangian gages were embedded in the distances of 30 - 36 mm, 20.9 - 26.9 mm and 11.1 - 17.1 mm, respectively.

The Pop-plot diagram, based on the values of distances to detonation obtained for the examined pressures of the shock wave, is shown in Fig.10.

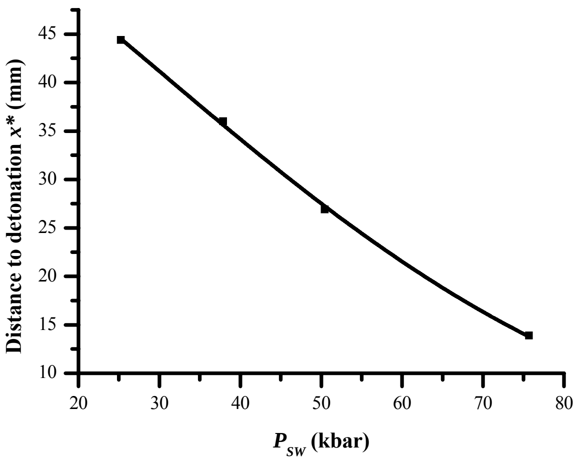
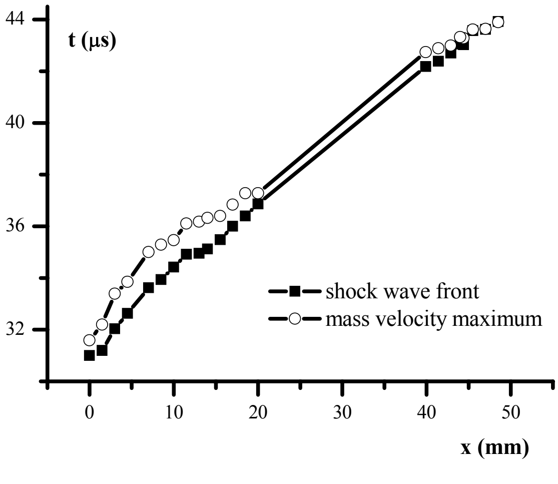
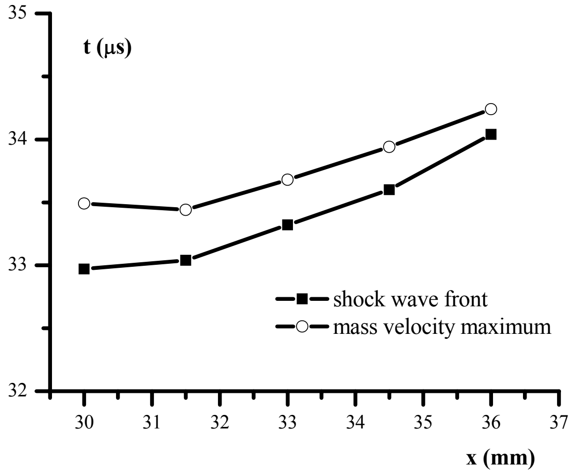


Figure 10. Pop-plot diagram for the LKE-11explosive compound

The trajectories of shock wave velocities and peak velocities for the LKE-11 explosive compound are shown in Fig.11. It is interesting to notice a mutual dependence of these two values for the intensity of the shock wave pressure of 25.25 kbar, Fig.11a), because there is stage IV, in which the peak mass values reach the shock wave front after x = 44 mm. For other shock wave pressure values, both trajectories are almost parallel from the second gage position (a higher increment has the shock wave velocity than the peak velocity for the pressure value P_{SW} of 37.89 kbar).



a)



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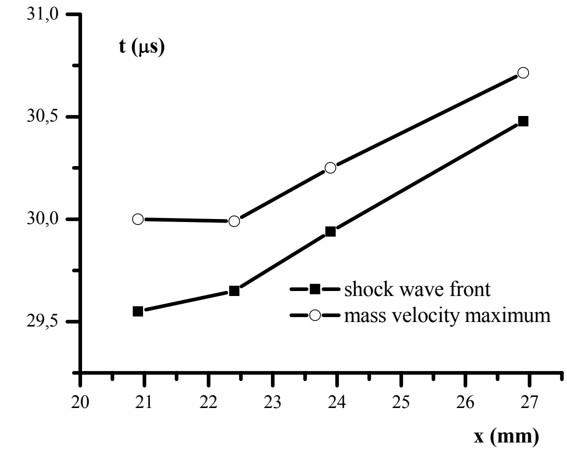

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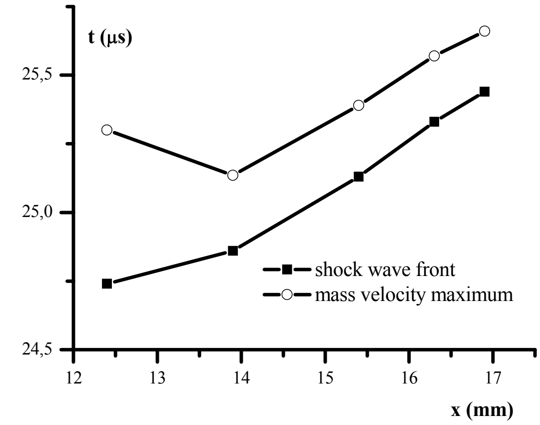


d)

Figure 11. Trajectories of shock wave velocities and peak mass velocities for LKE-11; PSW = 25.25 kbar (a), 37.89 kbar (b), 50.43 kbar (c) and 75.69 kbar (d)

The development of the detonation process in LKE-15 (HMX/AP/Al/HTPB 33/20/32/15) [19] by the shock wave of the pressure intensity of 24.32 kbar was examined in [14]. Based on the attenuator, the position x of electromagnetic gages was from 0 mm to 20 mm. It was concluded that there was not SDT for those x values, but a very rounded peak and the absence of the von Neumann spike can be seen. For SDT registering, the examination was done for the position x of 44.8 - 50.8 mm under the same shock wave pressure value. The registered $u(t)$ records are shown in Fig.12.

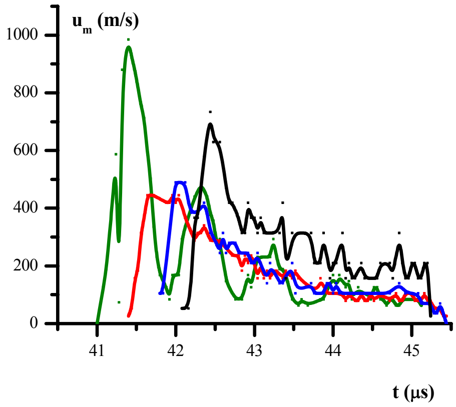


Figure 12. $u(t)$ records of the electromagnetic gages for x = 44.8 - 50.8 mm in the LKE-15 explosive charge under the intensity of shock wave pressure of 24.32 kbar

The detonation wave appearance and development are noticed for x^* = 50.8 mm, so the distance to detonation for the intensity of shock wave pressure of 24.32 kbar is 50.8 mm.

The explosive charge of LKE-15 was initiated by shock wave pressures of 36.49 kbar, 48.57 kbar and 72.90 kbar (around 1.5, 2 and 3 times higher than P_{SW} = 24.32 kbar) to obtain a Pop-plot diagram. The Lagrangian gages were embedded in positions of 35.0 - 41.0 mm, 25.8 - 31.8 mm and 14.2 - 20.2 mm, respectively.

The distance to detonation values in the function of shock wave pressure intensity are shown in Table 3.

It can be noticed that the decreased mass content of octogene in LKE-15 due to Al content increase has the distance to detonation x^* increasing as a consequence, as comparing the Pop-plot diagrams obtained for the LKE-11 and LKE-15 charges (for the same mass content of ammoniumperchlorate and HTPB binder), Fig.13. SDT for LKE-70/10 has the lowest values of x^*, first of all because of high octogene content, lower Al content and the absence of ammoniumperchlorate, the presence of which influences more a deviation from Zeldovich-von Neumman-Döring, so-called ZND detonation theory, i.e. the explosive is more un-ideal.

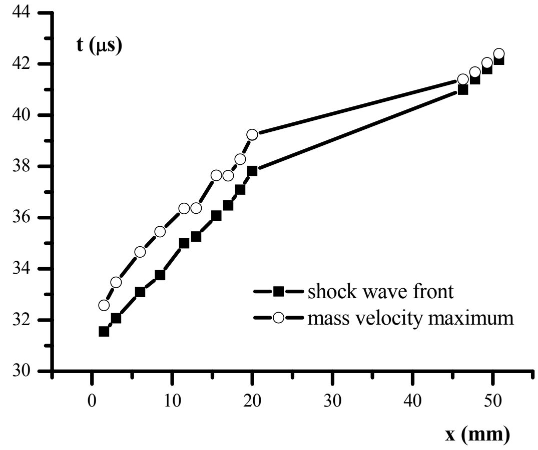
Table 3. LKE-15 – the distance to detonation in the function of the shock wave pressure intensity

P_{SW} (kbar)	x^* (mm)
24.32	50.8
36.49	39.5
48.57	28.8
72.90	17.2

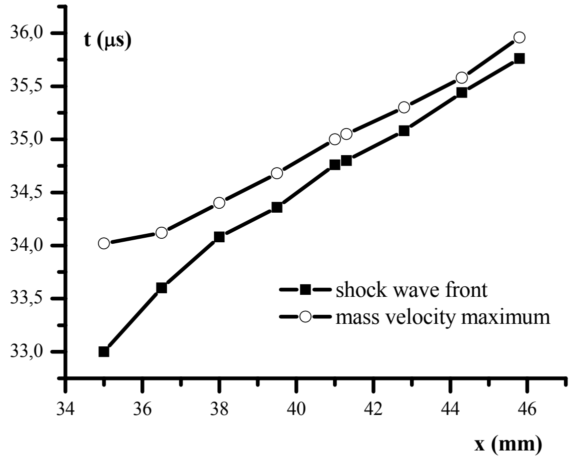
It is evident that the distance to detonation values obtained for high intensities of shock pressures, about three times higher than the critical pressure, are closed for all three compounds, because that pressure intensity is high enough to cause hot spots formation that would develop the detonation. The nature of "inert" additives to explosive comes to the fore for lower shock wave pressures - LKE-70/10 explosive compound, without ammoniumperchlorate addition, is much more sensitive (also, aluminium content is twice lower, and HTPB binder content is 20% wt, while it is 15% wt for other two compounds).

The shock wave velocity and peak mass velocity trajectories for the examined pressure intensities of the shock wave are shown in Fig.14. Stage IV, i.e. the trajectories match for higher distances x (higher than 46 mm), can be noticed in Fig.14a).

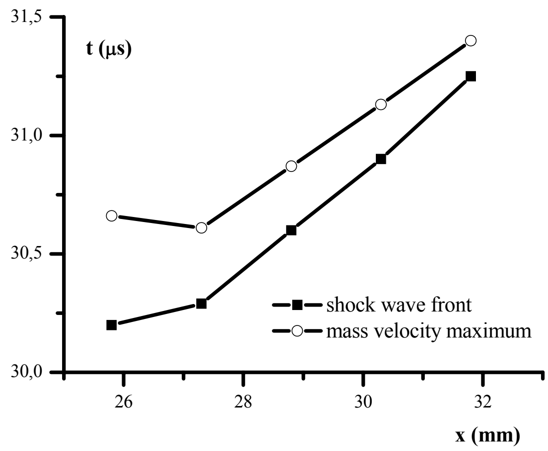
Generally, it can be concluded that a peak mass velocity increment for a trajectory is somehow lower than for the shock wave front, based on the analysis of data obtained by the examination of SDT in cast composite explosives. Based on the criterion of choosing the distance to detonation (the appearance of the first electromagnetic gage record with a high narrowed amplitude), the examination was not done for higher positions x, especially in the steady-state detonation region; therefore, stage V was not registered, i.e. the appearance of the von Neumann spike. Also, the period of time for which two trajectories are parallel decreases with the shock wave pressure increase; for example, for LKE-15 and P_{SW} = 24.32 kbar, the period lasts from 35-41.4 μs, and for P_{SW} = 72.9 kbar from 26-27.3 μs.



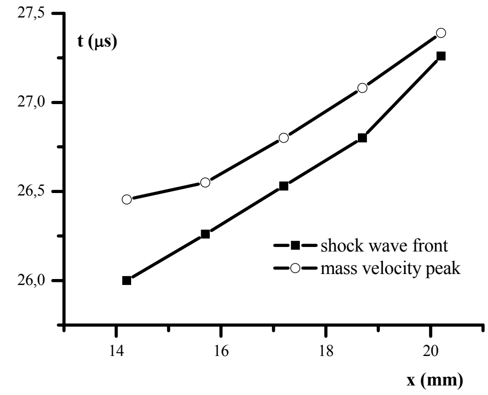
a)



b)



c)



d)

Figure 14. Trajectories of the shock wave velocities and the peak mass velocities for LKE-15; P_{SW} = 24.32 kbar (a), 36.49 kbar (b), 48.57 kbar (c) and 72.9 kbar (d)

SDT examination in pressed explosives

The development of the detonation process by the initiation of a shock wave of the same intensity, 25.44 kbar, was examined for pressed FH-5 and FP-5. The embedded electromagnetic gages were made of copper, 100 µm thick foil.

Pressed FH-5, ρ_0 = 1.594 g/cm^3, exposed to the action of a shock wave of the intensity of 25.44 kbar, was examined for the positions x from 0 mm to 12 mm; SDT begins for the value of x^* = 6 mm, so this is the distance to detonation, Fig.15.

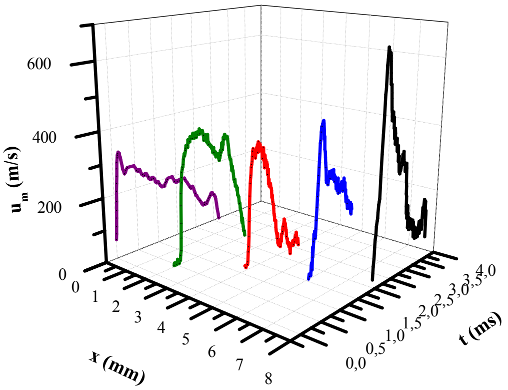


Figure 15. 3D view of the Lagrangian gage records for FH-5; PSW = 25.44 kbar

The view of two characteristic trajectories obtained for this pressure intensity, Fig.16, is very interesting. The data obtained for x = 16 mm and 20 mm are also presented; the difference in time for the same x values originates from the igniter – the induction time is 5 ± 0.5 µs [15]. Stages I and II are representative up to about 6 mm and in the depth x < 6 mm in the explosive charge the reaction is subsonic with respect to the shock wave. This small distance is obtained because the shock wave pressure is almost twice as high as the critical initiation pressure, P_{cr} = 11.33 kbar. For 6 mm alone, the electromagnetic gage record has the expressive peak, Fig.15, and there is the attenuation of the peak mass velocity trajectory; the reaction becomes supersonic. Also, stage IV is registered – the mass velocity peak, for around 16 mm, reached the shock wave front followed by mass velocity. Moreover, stage V is registered, e.g. the detonation with the von Neumann spike. Namely, the electromagnetic gage record for x = 20 mm, Fig.17, shows the particle velocity, $u_{CJ}(t)$, which is 1970 m/s for the density ρ_0 = 1.56 g/cm^3 of FH-5 explosive charge [22].

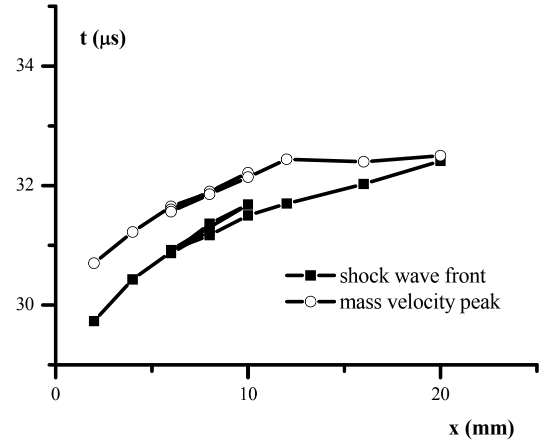


Figure 16. Trajectories of the shock wave velocities and the peak mass velocities for FH-5; P_{SW} = 25.44 kbar

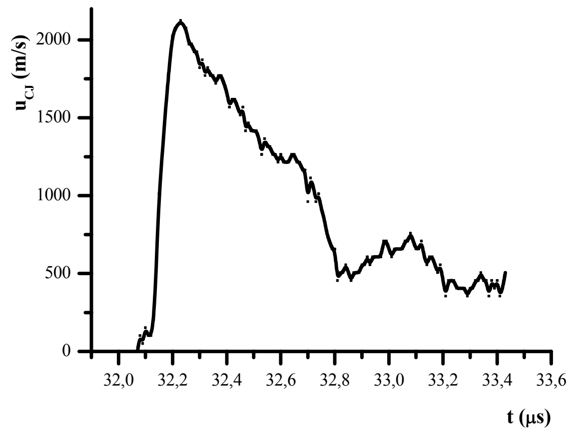


Figure 17. $u_m(t)$ for the position of x = 20 mm – $u_{CJ}(t)$ is registered

The SDT process was examined for the initiation of FH-5 under pressure of 12.72 kbar, 19.08 kbar and 38.04 kbar of the shock wave. The obtained results for the pressure intensity of 38.04 kbar are shown in Fig.18.

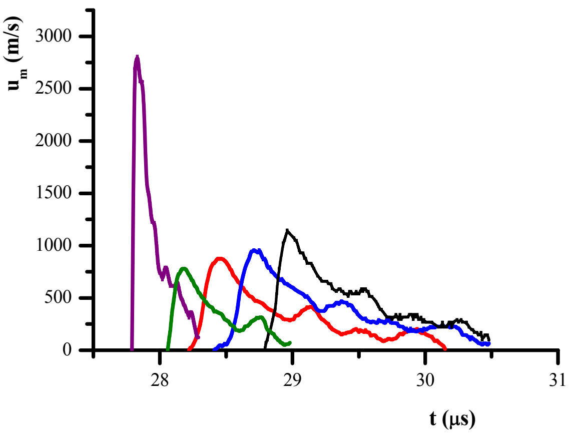


Figure 18. $u_m(t)$ for FH-5; PSW = 38.04 kbar

It is interesting to notice that SDT was examined first for the shock wave pressure of 12.72 kbar and the positions x from 8 - 16 mm and from 20 - 28 mm; the gage records are shown in Fig.19, and the mass velocity profiles are flat in shape, because the plane shock wave did not start to change under decomposition reaction in explosive charge appearing (it acts as an inert material). The distance to detonation is 42 mm for the shock wave pressure value of 12.72 kbar.

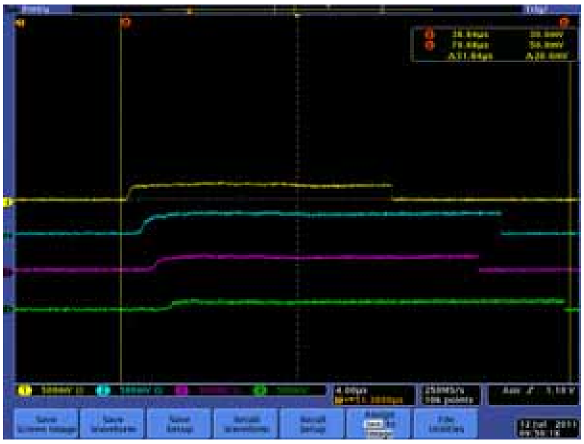


Figure 19. FH-5 – electromagnetic gage (number 2-5) records; P_{SW} = 12.72 kbar

Under the SDT examination for the pressure intensity of 38.04 kbar, the gage records shown in Fig.18 are obtained. Their analysis leads to the conclusion that the detonation is overdriven – the first gage registered the shock wave of high intensity, which decreased immediately after crossing to the explosive, and after x = 2 mm the shock wave again strengthens (supported by hot spot formation and by decomposition reaction); the distance to detonation x^* for this shock wave pressure is 2 mm.

The obtained distances to detonation for the used pressure values are shown in Table 4.

Table 4. FH-5 – distance to detonation in the function of the intensity of the shock wave pressure

P_{SW} (kbar)	x^* (mm)
12.72	42
19.08	18
25.44	6
38.04	2

The initiation of pressed FP-5, ρ_0 = 1.61 g/cm^3, by the shock wave of pressure 25.44 kbar was examined in [13]; the distance to detonation was x^* = 4 mm. In this paper the SDT process for the shock wave intensity of P_{SW} = 12.72 kbar (for x = 4 - 12 mm) and 19.08 kbar (first for x = 8 - 16 mm, and then for x = 4 - 12 mm) was examined. The results of the mass velocity measurement for higher pressures are presented in Fig.20.

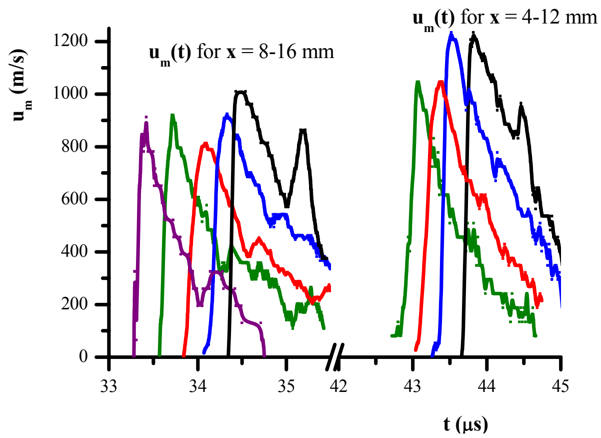


Figure 20. $u_m(t)$ for FP-5; PSW = 19.08 kbar

The values of distances to detonation for the used pressure intensities of the shock wave front are shown in Table 5.

Table 5. FP-5 – distances to detonation in the function of the shock wave pressure intensities

P_{SW} (kbar)	x^* (mm)
12.72	10
19.08	6
25.44	4

The fact that phlegmatized pentrite is more shock sensitive than FH-5 is confirmed in Fig.21: for the same shock wave pressures, smaller distances to detonation are obtained for FP-5 than for FH-5 explosive, especially in a lower pressure range. Pressed FP-5 is not examined for P_{SW} = 38.04 kbar (for FH-5 is obtained x^* = 2 mm for this pressure value), but tendency both Pop-plot diagrams indicates that they would be closed.

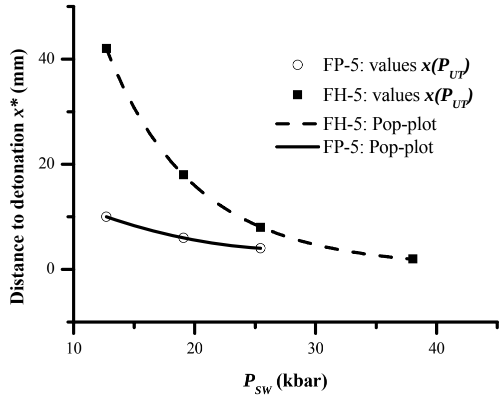


Figure 21. Compared view of the Pop-plot diagrams for the examined pressed explosives

Conclusion

The shock sensitivities of two cast composite compounds, LKE-11 (HMX/AP/Al/HTPB 40/20/25/15) and LKE-15 (HMX/AP/Al/HTPB 33/20/32/15), were determined in this paper by a modified GAP Test. It can be concluded that these two compounds have the same level of shock sensitivity. The critical pressure of LKE-11, the compound with a higher content of the explosive component, is a little lower. The modified GAP Test was also used for the determination of the shock sensitivity of two pressed explosives, FH-5 and FP-5. The results confirm higher sensitivity of phlegmatized pentrite.

The electromagnetic gage package was embedded in LKE-70/10 (HMX/Al/HTPB 70/10/20) cast composite explosive at different positions from the attenuator. Mass velocities were measured for the shock wave pressure intensities of 25.53 kbar, 38.04 kbar, 51 kbar and 76.55 kbar and the distance to detonation was determined for each pressure value. The obtained trajectories of the shock wave velocities, U, and the peak mass velocities, $u_m(max)$, were analyzed, indicating a subsonic reaction with respect to the shock wave for the positions x < 32.5 mm in the explosive charge; however, at 32.5 mm, the electromagnetic gage record has an expressive peak and the reaction becomes supersonic.

The Pop-plot diagram for the LKE-70/10 cast composite explosive was obtained based on the dependence of the distance to detonation in the function of the shock wave pressure intensity.

Mass velocity measures were done in the LKE-11 (HMX/AP/Al/HTPB 40/20/25/15) explosive under the shock wave pressures of intensities 25.25 kbar. Also, to obtain the Pop-plot diagram, the SDT process in the LKE-11 was examined for the shock wave pressures of 37.89 kbar, 50.43 kbar and 75.69 kbar.

The development of the detonation process in the LKE-15 (HMX/AP/Al/HTPB 33/20/32/15) was examined under the initiation by a shock wave of the intensity of 24.32 kbar for the position x = 44.8 - 50.8 mm, to register the detonation wave appearance. Pop-plot diagram was obtained for values of shock wave pressure of 36.49 kbar, 48.57 kbar and 72.90 kbar.

By analysing the Pop-plot diagrams obtained for the LKE-11 and LKE-15 explosive compounds, it can be concluded that the decreased content of octogene in the LKE-15 due to the increased Al content (for the same content of ammoniumperchlorate and HTPB binder) has increased distances to detonation as a consequence. For the LKE-70/10 explosive, with the highest explosive component content, SDT transition is for the smallest distances to detonation, which is the indirect proof that the detonation of the LKE with higher Al and oxydizer content deviates from the ZND theory of detonation, e.g. these explosives are non-ideal.

The distance to detonation values for all three LKE compounds are close for high shock wave pressure intensities, about three times higher than the critical pressure. For lower intensities of shock pressure, the content of "inert" additives to explosive is expressive, like ammoniumperchlorate – the LKE-70/10 explosive, without ammoniumperchlorate, is much more sensitive.

The pressed, FH-5, loaded by a shock wave of intensity of 25.44 kbar, was examined for the positions x from 0 mm to 8 mm; at 6 mm, the reaction becomes supersonic. The detonation wave with the von Neumann spike has been registered too, because the gage record for x = 20 mm shows the particle velocity profile. The SDT transition in FH-5 was also examined for the shock wave pressures of 12.72 kbar, 19.08 kbar and 38.04 kbar, in order to obtain the Pop-plot diagram.

The shock initiation in the FP-5 explosive charge was examined by the shock wave intensity of 12.72 kbar and 19.08 kbar. The obtained Pop-plot diagram was connected to the distance to detonation determination.

Higher shock sensitivity of phlegmatized pentrite with respect to FH-5 has been confirmed.

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Uticaj sastava i strukture eksploziva na razvoj procesa detonacije inicijacijom udarnim talasom

Rad obuhvata rezultate ispitivanja razvoja procesa detonacije eksploziva inicijacijom udarnim talasom dobijene u protekle tri godine. Najpre je definisana nova metoda, modifikovani GAP test, kojom se ispituje osetljivost eksploziva na inicijaciju udarnim talasom, a GAP sistem se sastoji od generatora ravnog udarnog talasa i oslabljivača od polietilena, čija je udarna adijabata određena. Ispitana je osetljivost eksplozivnih punjenja od FH-5 i FP-5 i livenog kompozitnog eksploziva LKE-11 i LKE-15 na inicijaciju udarnim talasom modifikovanim GAP testom. Proces inicijacije eksploziva udarnim talasom, IUT proces, ispitan je u livenom kompozitnom (LKE-70/10, LKE-11 i LKE-15) i presovanom eksplozivu (FH-5 i FP-5), pri različitim vrednostima pritiska udarnog talasa. Na osnovu analize dobijenih rezultata određeno je, za svaki eksplozivni sastav i intenzitet udarnog pritiska, rastojanje do detonacije, a zatim zavisnost rastojanja do detonacije u funkciji pritiska udarnog talasa ("Pop-plot" dijagram).

Ključne reči: **udarni talas, iniciranje detonacije, masena brzina, liveni eksploziv, presovani eksploziv, Lagranžova sonda, GAP test.**

Эффект состава и структуры взрывчатых веществ на развитие процесса инициирования детонации ударной волной

Данная статья содержит результаты исследования развития процесса детонации взрывчатых веществ инициированием ударной волной, полученные в последние три года. Во-первых определён новый метод, модифицированный GAP-тест, который проверяет чувствительность взрывчатых веществ на инициирование ударной волной, а GAP-система состоит из генератора плоской ударной волны и редуктора-панели из полиэтилена, чья ударная адиабата ярко определена. Мы исследовали чувствительность зарядов взрывчатых веществ от FH-5 и FP-5 и литых композитных взрывчатых веществ LKE-11 и LKE-15 на инициирование ударной волной модифицированным GAP-тестом. Процесс инициирования взрывчатых веществ ударной волной, IUT процесс, был испытан в литых композитных взрывчатых веществах (LKE-70/10, LKE-11 и LKE-15) и в сжатых взрывчатых веществах (FH-5 и FP -5), при различных значениях давления ударной волны. На основе анализа полученных результатов было определено для каждого взрывчатого состава и интенсивности скачков давления, расстояние до детонации а затем и зависимость расстояния до детонации в функции давления ударной волны ("Pop-plot" диаграмма).

Ключевые слова: **ударная волна, инициирование детонации, скорость частиц, литые взрывчатые вещества, сжатые взрывчатые вещества, зонд Лагранжевых, GAP тест.**

Influence de la composition et de la structure de l'explosif sur le développement du processus de la détonation par l'initiation de l'onde de choc

Les résultats des recherches sur le développement du processus de la détonation des explosifs par l'initiation de l'onde de choc obtenus au cours des trois dernières années ont été présentés dans ce papier. On a défini d'abord la nouvelle méthode, le test GAP modifié, par laquelle on examine la sensitivité de l'explosif à l'initiation par l'onde de choc. Le système GAP se compose du générateur de l'onde de choc plate et de l'atténuateur en polyéthylène dont l'adiabate de choc est définie. On a examiné aussi la sensitivité des charges explosives de FH-5 et FP-5 ainsi que l'explosif de fonte composite LKE-11 et LK-15 à l'initiation de l'onde de choc par le test GAP modifié. Le processus de l'initiation de l'explosif par l'onde de choc , processus IUT, a été examiné pour les explosifs composites de fonte (LKE- 70/10, LKE -11 et LK-15) et pour les explosifs pressés (FH-5 et FP-5) pour les différentes valeurs de la pression de l'onde de choc. A la base de l'analyse des résultats obtenus on a déterminé pour chaque composition de l'explosif et chaque intensité de l'onde de choc la distance de la détonation en fonction de la pression de l'onde de choc (« Pop-plot « diagramme).

Mots clés: **onde de choc, initiation de détonation, vitesse des particules, explosif de fonte, explosif pressé, sonde de Lagrange, test GAP.**