



Theoretical paper / Praca teoretyczna

Detonation velocity and energetic potential of low density explosive charges

Prędkości detonacji i potencjały energetyczne ładunków o obniżonej gęstości właściwej

Andrzej Maranda^{1,*}, Andrzej Papliński²

¹) Łukasiewicz Research Network – Institute of Industrial Organic Chemistry,
6 Annapol St., 03-236 Warsaw, Poland

²) Military University of Technology, Faculty of Mechatronics, Armament and Aerospace,
2 gen. S. Kaliskiego St., 00-908 Warsaw, Poland

* E-mail: andrzej.maranda@ipo.lukasiewicz.gov.pl

ORCID Information:

Maranda A.: 0000-0003-3543-6587

Papliński A.: 0000-0001-5286-3682

Abstract. In the paper, the employment and energetic performance of explosive charges of low detonation velocity is considered. Explosives based on ammonium nitrate were investigated. Energetic performance was enhanced by the addition of aluminium powder. Detonation velocity adjustment was attained by the introduction of inert additives, glass balloons or SiO₂ in colloidal form. Detonation velocity changes in the range of 1700 down to 900 m/s were observed. Thermodynamic analysis of the energetic effectiveness of the investigated explosives was carried out. It was found that the heat of explosion of explosive mixtures containing 3% or 6% of powdered aluminium reaches 2.2 and 3.1 MJ/kg, respectively. The obtained results confirm that the investigated explosive charges may be successfully implemented in practical applications in which the magnitude of the detonation velocity is to be controlled.

Streszczenie. W pracy rozpatrzone zostały zagadnienia efektywności energetycznej ładunków wybuchowych o obniżonej prędkości detonacji. Rozpatrywano materiały wybuchowe na bazie saletry amonowej, wydatek energetyczny był modyfikowany dodatkiem proszku aluminium. Prędkość detonacji badanych materiałów wybuchowych regulowana była inercyjnym dodatkiem mikrosfer szklanych lub SiO₂ w formie koloidalnej. Uzyskano zmianę prędkości detonacji w zakresie od 1700 do 900 m/s. Przeprowadzono analizy termodynamiczne w celu określenia efektywności energetycznej badanych materiałów wybuchowych. Stwierdzono, że w przypadku materiałów zawierających 3% i 6% proszku aluminium osiągnięte ciepło wybuchu jest odpowiednio rzędu 2,2 i 3,1 MJ/kg. Potwierdza to możliwość praktycznego zastosowania ładunków badanych materiałów wybuchowych w przypadku, gdy zachodzi potrzeba sterowania prędkością detonacji.

Keywords: low-detonation-velocity explosives, aluminised explosives, heat of explosion

Słowa kluczowe: materiały o obniżonej prędkości detonacji, aluminizowane materiały wybuchowe, ciepło wybuchu

1. Introduction

In homogeneous explosives, and if the leading explosive compound is supplemented with modifiers (e.g. PBX), there is a good relation and dependency between the detonation velocity (D) and explosion energy. In many cases, particularly in military applications, it is advantageous to find and use explosive charges with high D and energy [1]. However, the requirements of technical applications are varying, for example in explosive rock quarrying, explosive plating, tubes fitting in heat exchanger bottoms [2, 3]. In such cases, the lower D has an advantageous effect on the generated waveform of the loaded medium.

In the case of explosive charges placed in bore-holes, high D results in intense, abrupt overpressure changes at the front of stress waves generated by the moving front of the detonation wave. This leads to disadvantageous effects in the rock quarrying process. The intense stepwise overpressure waves are generated, which leads to the development of zones of excessive fragmentation, rock crushing, while the resulting uneven load field distribution is a cause of irregular fragmentation and production of oversized rock aggregates. In the case of charges with reduced D , when the D becomes subsonic in relation to the loaded rock, the elementary pressure waves generated at the front of the detonation wave overtake the detonation wave. This prevents the generation of abrupt parameter changes at wave fronts progressing in loaded medium [4, 5].

The selection and reduction of the D were the subjects of extensive research. One of the tested subjects are explosives obtained by addition of cooling salts which reduce the temperature of detonation products [6]. In this case, the low D also improves the safety of rock shooting works in the presence of combustible atmospheres, e.g. in methane filled road heads. The research to find low-detonation-velocity explosives is also conducted independent of indication of the direct areas of application. In [7], the D was reduced to 890, 840, 880, 810 m/s, respectively, by addition of the lead oxides, PbO_2 and Pb_3O_4 .

The test results of the low D obtained by the addition of potassium chloride (KCl) and monoammonium phosphate ($NH_4H_2PO_4$, MAP) to ammonium nitrate(V) (AN) are presented in [8]. The addition of 10% KCl resulted in a D of 1420 m/s, while the addition of 15% MAP resulted in a velocity of 1290 m/s. By increasing the percentage of additives, a further reduction of the D was obtained, down to approx. 1200 m/s, until no actuation. The study delivers no estimates of the influence of the low D on the temperature decrease in detonation products.

There is continuing interest in research on explosives designed for explosive metal bonding. One of the latest studies in this field is [9], in which further quotations of literature sources may be found. The focus of [9] is the experimental and numerical analysis of the bond formation process. Proper bonding was obtained by using an emulsion explosive with a D of 2500 m/s.

The presented paper undertakes analysis of the effect of the physical structure of components on reduction of the D . AN-based aluminised explosives with added silicon oxide (SiO_2) in various physical forms were investigated. The purpose of the study was, in particular, to compare the effect of the introduction of the same chemical compound (SiO_2) in glass microsphere form and in colloidal form, on the explosive transformation characteristics. The surface structure, sub-cavities and pores at the added silica grains are, to a certain degree, involved in the detonation sustaining mechanism. This effect is undoubtedly different from the investigated hot spot formation mechanisms in the shock compression of glass microspheres. Without going into a detailed investigation of these mechanisms, which exceeds the scope of the present study, the analysis on how such additives impact detonation and explosion macro-parameters was carried out.

Consistent with the known properties of AN, in most charges based on AN the detonation process becomes non-ideal in nature. The critical diameter (d_{kr}) of AN with a specific density (ρ_0) in the order of 0.9 g/cm³ reaches 30 cm [10]. The additives considered in the study support the non-ideal nature of the transformation process. In particular, the addition of aluminium (Al) powder increases the amount of energy released beyond the Chapman-Jouguet (C-J) plane. Therefore, in the analysis of the considered explosive mixtures, significant differences between the values recorded experimentally and the ideal detonation velocities, which may be calculated using thermochemical codes, should be expected. On the other hand, extending the

energy release process has an positive effect on the generated waveform of the load field [2-5]. Therefore, the ideal D and parameters do not constitute the full characteristics, defining the practical capabilities of this type of low-detonation-velocity charge.

In view of that, in performed analysis the heat of explosion at constant volume is regarded as the dominant energy parameter of the explosives tested. It corresponds to the full use of potential explosion energy by e.g. rock blasting.

The first subsection of the study presents the chemical composition and the experimentally recorded results, while the second subsection presents thermodynamic calculation results. The ideal D (D_{cv}), heat of explosion at constant volume (Q_v) and gaseous explosion product volume (V_{gas}) were estimated. The oxygen balance (B_T) values for the individual mixtures are also quoted. Experimental data of the analysed explosives were taken from [11].

2. Low-detonation-velocity charges – characteristics and experimental results

Tables 1 and 2 show the experimental results obtained for mixtures containing of 3% and 6% (by weight) of flaked Al powder. Inert additives in glass microsphere form and colloidal silica (SiO_2) form were considered. An increase in Al content increases the D of investigated mixtures. At the same time obtained experimental registrations indicate observable decrease of the d_{kr} by increase in Al powder content. In both cases, the D was measured for charges with diameters greater than the d_{kr} of the considered explosive charge. Al powder was used in flake form to increase the conversion rate.

Table 1. Detonation parameters of charges with Al dust and glass microspheres content [11]

| Sample no. | 1 | 2 | 3 | 4 | 5 | 6 |
|-------------------------------|------|------|------|------|------|------|
| AN [wt.%] | 92.0 | 87.0 | 82.0 | 89.0 | 84.0 | 79.0 |
| Al dust [wt.%] | 3.0 | | | 6.0 | | |
| Glass microspheres [wt.%] | 5.0 | 10.0 | 15.0 | 5.0 | 10.0 | 15.0 |
| ρ_0 [g/cm ³] | 0.99 | 0.90 | 0.85 | 0.96 | 0.93 | 0.85 |
| d_{kr} [mm] | 11 | 15 | 18 | 10 | 12 | 16 |
| Charge diameter (d) [mm] | 18 | | | | | |
| D [m/s] | 1560 | 1280 | 1060 | 1600 | 1490 | 1150 |

Table 2. Detonation parameters of charges containing Al dust and silica (SiO_2) in colloidal form [11]

| Sample no. | 7 | 8 | 9 | 10 |
|-------------------------------|------|------|------|------|
| AN [wt.%] | 92.0 | 89.5 | 89 | 86.5 |
| Al dust [wt.%] | 3.0 | | 6.0 | |
| SiO_2 [wt.%] | 5.0 | 7.5 | 5.0 | 7.5 |
| ρ_0 [g/cm ³] | 0.46 | 0.40 | 0.46 | 0.37 |
| d_{kr} [mm] | 12 | 17 | 12 | 15 |
| d [mm] | 25 | | | |
| D [m/s] | 1700 | 990 | 2230 | 1450 |

3. Low-detonation-velocity charges – thermodynamic interpretation

The first set of calculations was performed for materials modified with glass microspheres. It was assumed that the properties of the substance forming the microspheres are represented by SiO_2 . The calculations accounted for the heat absorption of the material forming the microspheres (SiO_2). Figure 1 shows the specific heat of SiO_2 compared to the specific heat of carbon dioxide (CO_2). Apparently, the inertial action

of SiO_2 in relation to the negative accumulation of a part of the explosion energy is moderate and the heat absorption corresponds to the internal energy of one of the main explosion products, i.e. CO_2 .

For comparison purposes, Figure 1 includes the specific heat of CO_2 at constant pressure (c_p) and at constant volume (c_v). Due its negligible compressibility, only the c_p is given for SiO_2 . Figure 1 shows the phase transition, which occurs at a temperature of 1200 K for SiO_2 , and melting, which occurs at 1996 K.

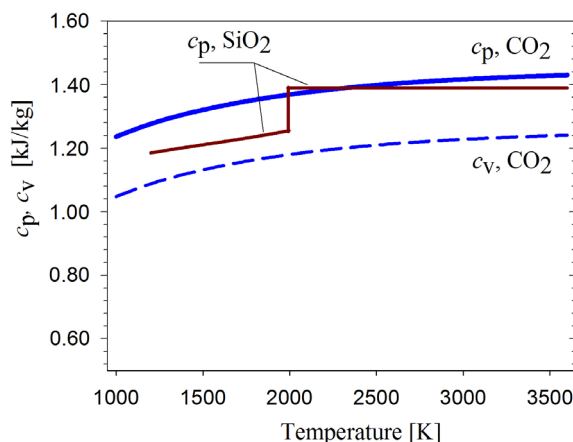


Figure 1. Comparison of the specific heat of (silica) SiO_2 with that of CO_2

For Al powder, the calculations accounted for the presence of the Al oxide (Al_2O_3) layer covering the powder grains. It was assumed that the Al_2O_3 content was 6 wt.%. The covering layer of Al grains was considered as a second inert component, as in the case of SiO_2 .

The detonation and explosion parameters calculated for charges with Al dust and glass microspheres content, in relation to the basic characteristics of the investigated charges, are presented in Table 3.

Table 3. Detonation and explosion parameters of charges with Al dust and glass microspheres content

| Sample no. | 1 | 2 | 3 | 4 | 5 | 6 |
|--------------------------------------|-------|-------|-------|-------|-------|-------|
| AN [wt.%] | 92.0 | 87.0 | 82.0 | 89.0 | 84.0 | 7.09 |
| Al dust [wt.%] | 3.0 | | | 6.0 | | |
| Glass microspheres [wt.%] | 5.0 | 10.0 | 15.0 | 5.0 | 10.0 | 15.0 |
| ρ_0 [g/cm ³] | 0.99 | 0.90 | 0.85 | 0.96 | 0.93 | 0.85 |
| d_{kr} [mm] | 11 | 15 | 18 | 10 | 12 | 16 |
| d [mm] | 18 | | | | | |
| Experimental D (D_{exp}) [m/s] | 1560 | 1280 | 1060 | 1600 | 1490 | 1650 |
| B_T [%] | 15.88 | 14.88 | 13.88 | 12.27 | 11.77 | 10.77 |
| D_{ev} [m/s] | 4220 | 3770 | 3450 | 4240 | 3965 | 3550 |
| Q_v [MJ/kg] | 2.325 | 2.246 | 2.166 | 3.114 | 3.087 | 2.983 |
| V_{gas} [dcm ³ /kg] | 965 | 912 | 858 | 914 | 860 | 807 |

Q_v designates the heat of explosion at constant volume, while V_{gas} represents the final volume of gaseous explosion products after expansion to ambient pressure ($p_0 = 0.101325$ MPa). As can be seen, the ideal values of the D significantly exceed the values observed experimentally, which results from the extensive zone of the chemical reactions which follow the front of the detonation wave. A graphic interpretation of the obtained results is shown in Figures 2 and 3. Figure 2 illustrates the changes in Q_v in relation to the experimental and calculated ideal detonation velocities. In turn, in Figure 3 shows the Q_v values in relation

to the ρ_0 of the tested charges, along with the specific volume of explosion products, considering the ρ_0 of the investigated charges and detonation velocities observed experimentally.

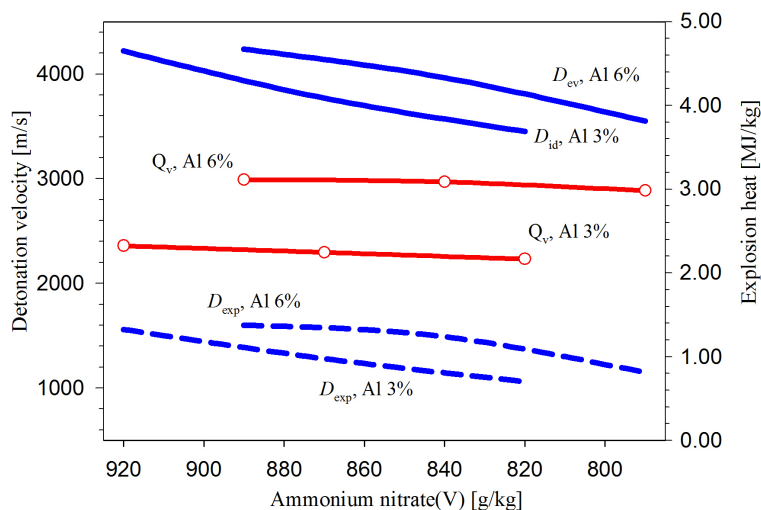


Figure 2. Analysis of the D and Q_v of low-detonation-velocity charges induced with the addition of glass microspheres: D_{exp} – observed D , D_{ev} – forecast ideal D at full conversion of the mixture before point C-J

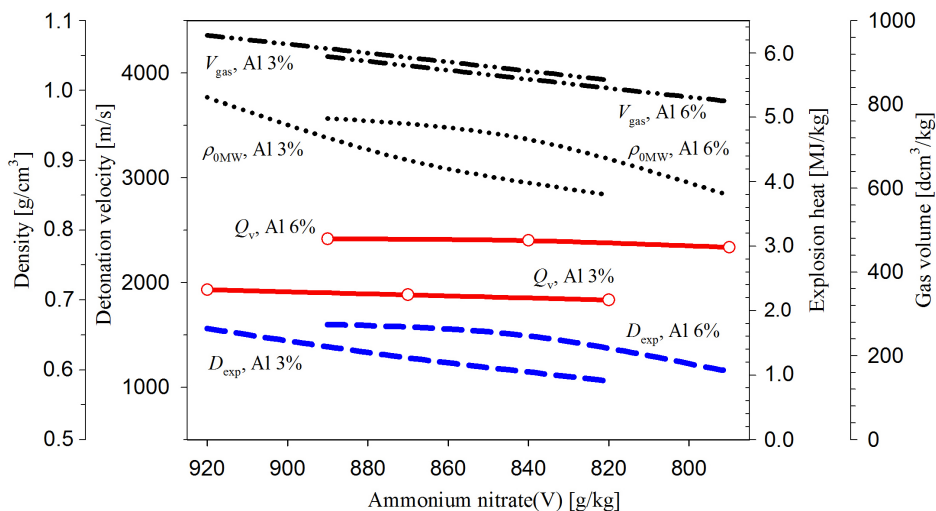


Figure 3. Selected transformation parameter characteristics of low-detonation-velocity charges induced with the addition of glass microspheres, ρ_{0MW} – specific density of the charge, V_{gas} – volume of explosion products, other symbols as in Figure 1

Figures 2 and 3 confirm the positive effect of the addition of Al powder in terms of energy. An increase in Al content increases the D . The relatively high volume of gaseous detonation products should be noted which, supported by the explosion energy value determines the potential work capacity of the expanding transformation products. The basic characteristics and calculated transformation parameters of charges with

silica (SiO_2) content in colloidal form are presented in Table 4. A graphic interpretation of the obtained results is presented in Figures 4 and 5.

Table 4. Detonation and explosion parameters of charges containing Al dust and silica (SiO_2) in colloidal form [11]

| Sample no. | 7 | 8 | 9 | 10 |
|--|-------|-------|-------|-------|
| AN [wt.%] | 92.0 | 89.5 | 89.0 | 86.5 |
| Al dust [wt.%] | 3.0 | | 6.0 | |
| Silica [wt.%] | 5.0 | 7.5 | 5.0 | 7.5 |
| ρ_0 [g/cm^3] | 0.46 | 0.40 | 0.46 | 0.37 |
| d_{kr} [mm] | 12 | 17 | 12 | 15 |
| d [mm] | 25 | | | |
| D_{exp} [m/s] | 1700 | 990 | 2230 | 1450 |
| Oxide balance (B_T) [%] | 15.88 | 15.38 | 12.77 | 12.27 |
| D_{ev} [m/s] | 2746 | 2538 | 2848 | 2571 |
| Q_v [MJ/kg] | 2.320 | 2.228 | 3.133 | 3.094 |
| V_{gas} [dcm^3/kg] | 965 | 938 | 914 | 887 |

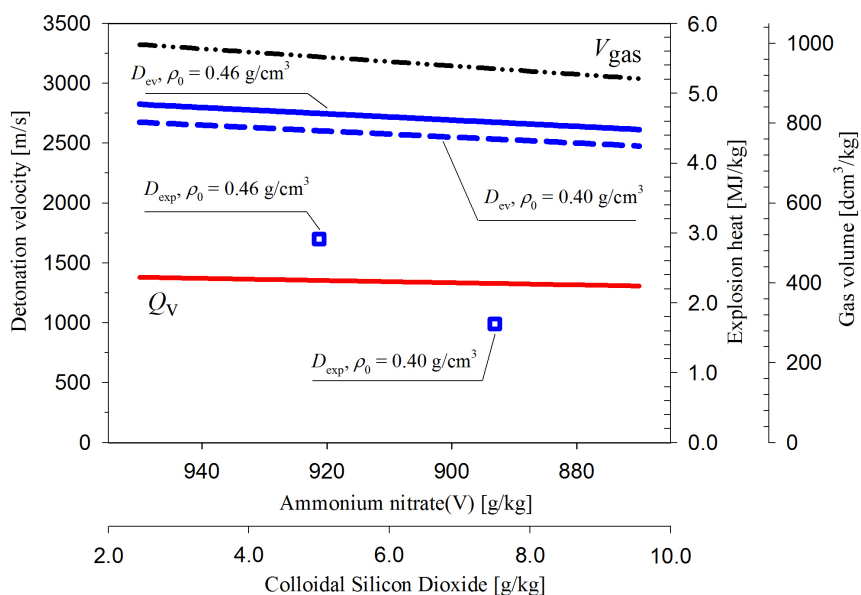


Figure 4. Analysis of transformation parameters of charges containing silica in colloidal form with 3% Al powder content: D_{exp} – observed D , D_{ev} – forecast ideal D at full conversion of the mixture before point C-J, Q_v – heat of explosion, $\rho_{0MW} = 0.46 \text{ g}/\text{cm}^3$, V_{gas} – volume of explosion products, $\rho_0 = 0.46 \text{ g}/\text{cm}^3$

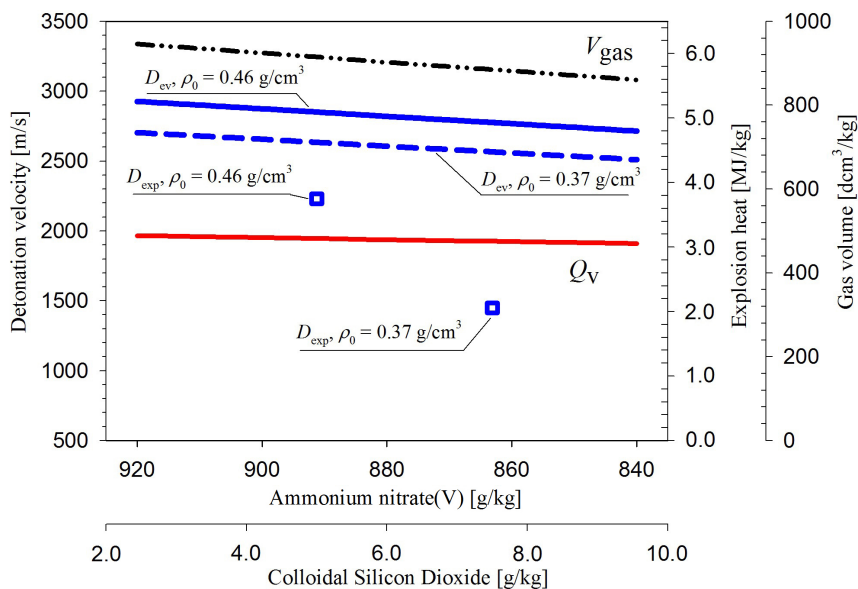


Figure 5. Analysis of transformation parameters of charges containing silica in colloidal form with 6% Al powder content (symbols as in Figure 4)

The results prove the significant effect of silica in powdered form on detonation parameters, in particular on the recorded D values. It should be noted that for the D determined theoretically, the effect of silica content is regular, within the considered SO_2 content range, i.e. from 2% to 10%. Similarly, the values of other transformation parameters, such as explosion heat or the volume of gaseous explosion products, which correspond to the transformation products in chemical and thermodynamic equilibrium, monotonically depend on the silica content (Figures 4 and 5).

However, the D values observed experimentally for silica in powdered form change significantly with a fifty percent increase in powder content from 5% to 7.5%. Hence it may be concluded that the physical structure of inert additive grains, namely silica in powdered form in the considered cases, the surface and subsurface structure of the grains introduced may have an effect on the transformation dynamics in the detonation zone. The comparison of the results obtained for microspheres and silica in powdered form indicates some potential possibilities to adjust the detonation parameters, in particular the D , by various ways of mechanical sensitisation of the explosive.

4. Summary

- ◆ The study comprised the analysis of the effect of two silica forms, glass microspheres and powder, on the detonation process of AN-based explosives. Mixtures with 3% and 6% Al powder content were considered.
- ◆ D change in the range of 1700 down to 900 m/s was observed. Thermodynamic analysis of the energetic effectiveness of the investigated explosives was carried out. It was found that the explosion heat of explosive mixtures containing of 3% or 6% of powdered Al reaches 2.2 and 3.1 MJ/kg, respectively. It may be considered that for mixtures with at least 6% Al powder content, practical application options emerge for the tested explosives.
- ◆ The summary of the experimental results and quantitative analyses shows a significant potential role of the physical structure of the inert additive introduced to the energy mixture. For glass microspheres, quasi-linear dependencies of detonation and explosion parameters on the microspheres content are found (Table 3, Figures 2 and 3). For silica in powder form, changing the additive content from 5.0% to 7.5%

results in a very significant change of the D . This enables concluding that silica grains influence the transformation, without direct involvement in the chemical reactions in the detonation zone. Examining the specifics of this interaction requires further extended research.

- ◆ The materials tested were characterised by a positive oxygen balance. In terms of energy efficiency, this creates a potential to further increase the explosion energy by introducing a higher share of the fuel (Al powder). However, it may be noticed that an increase in the transformation energy will imply an increase in the D . If D control is required to obtain an intended lower range, the results presented in the study may serve as reference.
- ◆ In addition, as stated by the authors of [12], an increase in the oxygen balance of systems with quartz sand content causes an increase in the potential of the explosion products to cause ignition of the combustible atmosphere (methane and air), in which the detonation occurs. As noted in [2], the authors of [12] did not undertake to discuss the interaction mechanism of quartz inclusions on the explosive transformation process.
- ◆ The transformation of systems with a clear positive oxygen balance reduces the possibility of generation of incomplete combustion products [13], such as CO, OH, NO, aldehydes and other, which could form ignition centres for the combustible atmosphere, into which they are released. Hence, the compositions proposed in the study enable obtaining a satisfactory energy expenditure, while retaining the application safety level.

References

- [1] Cudziło S., Maranda A., Nowaczewski J., Trębiński R., Trzcziński W.A. *Military Explosives*. Częstochowa: Wyd. Wydziału Metalurgii i Inżynierii Materiałowej Politechniki Częstochowskiej, **2000**.
- [2] Maranda A. *Industrial Explosives*. Warsaw: Wyd. Wojskowa Akademia Techniczna, **2010**.
- [3] Babul W. *Deformation of Metals by Explosion*. Warsaw: Wyd. Naukowo-Techniczne, **1980**.
- [4] Misiak P., Papliński A., Włodarczyk E. Cylindrical Stress Waves in Elastic Medium Generated by a Moving Axisymmetrical Super-seismic Pressure Pulse. *J. Techn. Phys.* **1976**, *17*(3): 305-314.
- [5] Papliński A., Włodarczyk E. Stress and Displacement Fields Generated by a Distributed Load, Moving with a Constant, Underseismic Velocity Along the Cylindrical Bore in the Isotropic Elastic Medium. *J. Techn. Phys.* **1980**, *21*(2): 225-243.
- [6] Papliński A., Maranda A. Investigation of the Influence of Cooling Salts upon the Explosive Performance of Emulsion Explosives. *Cent. Eur. J. Energ. Mater.* **2015**, *12*(3): 523-536.
- [7] Maranda A., Cudziło S. Explosives Mixtures Detonating at Low Velocity. *Propellants Explos. Pyrotech.* **2001**, *26*(3): 165-167.
- [8] Tan L., Xia L.H., Wu Q.J., Xu S., Liu D.B. Detonation Characteristics of Ammonium Nitrate and Activated Fertilizer Mixtures. *Combust. Explos. Shock Waves* **2016**, *52*(3): 335-341.
- [9] Xu M., Xie X., Wang H., Zhu M. Experimental Study and Numerical Simulation of Explosive Welding of Nickel Foil with Q235 Steel. *Cent. Eur. J. Energ. Mater.* **2023**, *20*(3): 241-259; <https://doi.org/10.22211/cejem/172909>.
- [10] Der VanSteen A.C., Kodde H.H., Miyake A. Detonation Velocities of the Non-ideal Explosive Ammonium Nitrate. *Propellants Explos. Pyrotech.* **1990**, *15*(2): 58-61.
- [11] Maranda A. Research of Development of Explosive Material for Mining Block Deposits. *Przegląd Górniczy* **1998**, *54*(3): 25-29.
- [12] Dubnov L.W., Bacharewicz N.S., Romanov A.I. *Industrial Explosives*. (in Russian) Moskva: Izd. Nedra, **1973**.
- [13] Rychter T., Teodorczyk A. *Car Engine Theory*. Warsaw: Wyd. Komunikacji i Łączności, **2006**.

Received: September 11, 2023

Revised: December 19, 2023

First published on line: December 21, 2023