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Research paper / Praca doświadczalna

Influence of ammonium nitrate(V) grain size on the detonation parameters of ammonals
Wpływ wielkości ziaren azotanu(V) amonu na parametry detonacji amonali

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Abstract: *An investigation into the effect of particle size of ammonium nitrate(V) on the pressure and velocity of detonation of ammonals with a fixed aluminium powder content, was carried out. Piezoresistive manganin pressure sensors were used to measure the detonation pressure and short-circuit sensors were used to measure the detonation velocity. The velocity of detonation and the density of ammonals increase with the extent of ammonium nitrate(V) fragmentation. The highest value of detonation pressure was obtained at the 200-300 μm fraction.*
Streszczenie: *W pracy podjęto próbę zbadania wpływu rozdrobnienia azotanu(V) amonu na ciśnienie i prędkość detonacji amonali o stałej zawartości dodatku proszku aluminium. W badaniach wykorzystano piezorezystancyjne manganinowe czujniki ciśnienia do pomiaru ciśnienia detonacji oraz metodę czujników zwarciowych do pomiaru prędkości detonacji. Prędkość detonacji i gęstość amonali rosną wraz ze stopniem rozdrobnienia azotanu(V) amonu. Najwyższą wartość ciśnienia detonacji zmierzono dla frakcji 200-300 μm.*

Keywords: *detonation pressure, manganin pressure gauges, amonals*
Słowa kluczowe: *ciśnienie detonacji, manganinowe czujniki ciśnienia, amonale*

1. Foreword

The non-ideal nature of detonation of ammonium nitrate based explosives means they are highly dependent on the physical and chemical properties of the components of the composition. This group of explosives include the ammonals (oxidiser – fuel system), a loose mixture of ammonium nitrate(V) (AN, NH_4NO_3) and aluminium powder. The basic processes occurring during detonation include the exothermal decomposition of AN and the oxidation of aluminium in a wide chemical reaction zone within the detonation wave. A decrease in particle size of the components changes the dominant process (due to its calorific value) of the detonation to aluminium oxidation with AN decomposition products [1, 2]. In [2-5], the authors studied the effect of AN particle sizes on the detonation velocity of selected ammonals of identical composition.
In [2], identical mixtures but with different AN particle sizes were prepared. Two types of AN with particle size of 0.075 to 0.300 mm and 0.9 to 1.7 mm were used. Tubes with a 10 cm diameter were filled with the compositions. A detonation velocity, higher by approx. 1000 m/s, was obtained for charges containing the

smaller particle size AN. A similar correlation was also observed in [3, 4]. Ground and dried AN sifted into different fractions was used. The study showed that for compositions with a constant amount of aluminium powder, a decrease in AN particle size increases the detonation velocity. In [6], the authors presented the detonation velocities of ammonals measures using two different methods: continuous measurement and point measurement. The compositions were prepared using fine AN, sifted through a 800 μm mesh and dried in an incubator. Two aluminium powder types were used. The results for the analysed ammonals showed that the detonation velocity increases with an increase in aluminium powder content. Simultaneously, the detonation velocity decreases with a decrease in particle size of the combustible component.
The study aimed to analyse the changes in detonation pressure depending on the particle size of AN for a constant aluminium powder content.

2. Experimental section

2.1. Tested materials

2.1.1. Ammonium nitrate(V)

Porous AN, manufactured by Yara Poland Sp. z o.o., was used in the study. The porous AN size was reduced in a RETSCH ZM 200 ultra-centrifugal mill with cyclone separator [3]. The next stage involved separating the ammonium nitrate(V) particles into different fractions using a combination of vibrating sieves with different mesh sizes. The following sieve meshes were used: 800, 710, 600, 500, 400, 300, 200, 100 μm. The Retsch AS200 controlled 'g' sieve shaker was used to determine the particle-size distribution and separate the material into fractions. The ground AN was sifted in 500 g portions by shaking for 5 min at an amplitude of 1.5 mm/g without any intervals, yielding different ammonium nitrate(V) fractions with different particle size. Figure 1 shows the % weight fraction obtained for each mesh size.

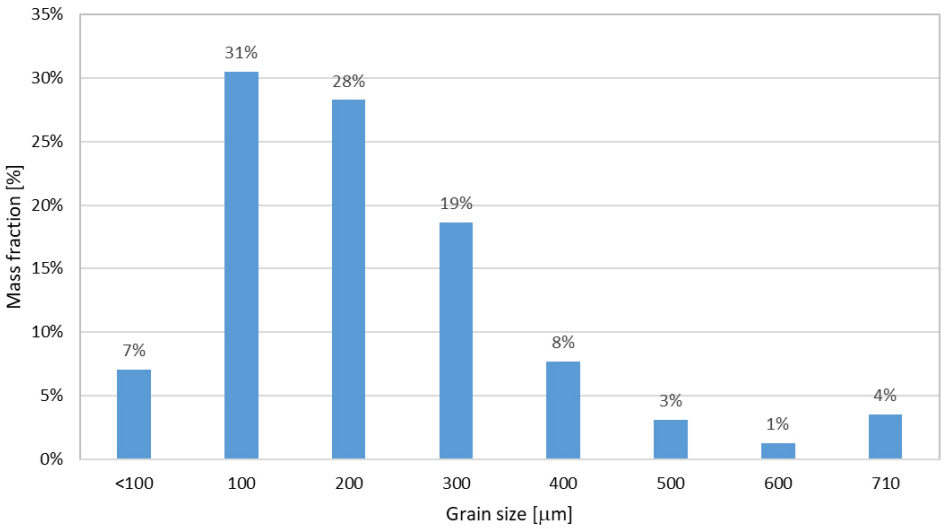


Figure 1. Percentage share of ammonium nitrate fractions with different particle sizes

2.1.2. Aluminium powder (Al_f)

Aluminium powder by Benda-Lutz (Figure 2), whose specifications are shown in Table 1, was used as the fuel. The benefits of using this type of aluminium powder is that it includes non-dusting, small flake-shaped particles which limit dispersion and prevent separation of the composition's components.

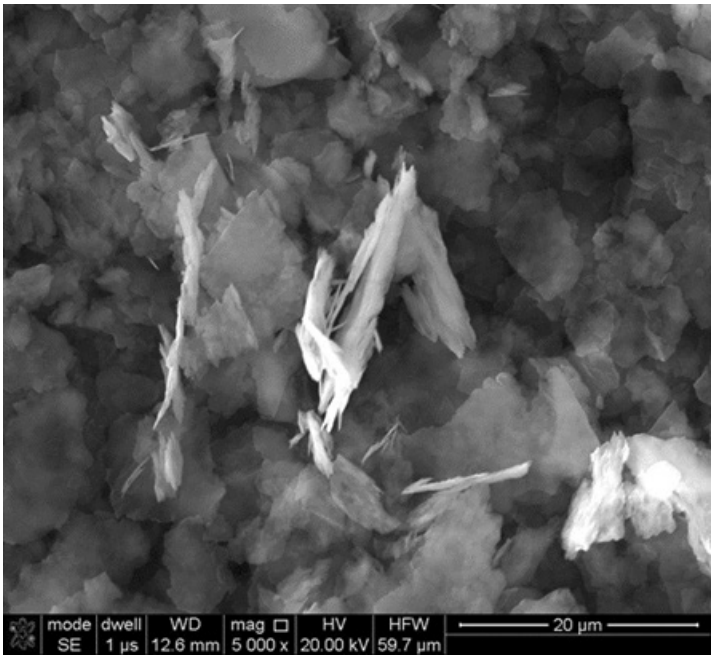


Figure 2. SEM image of the aluminium powder Al_f used

Table 1. Specification of Benda-Lutz DEPUVAL non-dusting aluminium powder – Al_f

Property	Unit	Value
Catalogue number	–	3083
Aluminium content	[%]	99.7
Coating surface	[cm^2/g]	29000
45 µm mesh fraction	[%]	0.8
Average particle size	[µm]	12
Bulk density	[kg]	0.4

2.1.3. Tested explosive compositions

After sieving, the following AN fractions were selected for further tests: 710-400, 400-300, 300-200, 200-100 and <100 µm. The effect of AN particle size on the detonation velocity was analysed using ammonal with 10% Al_f content. Each composition was homogenised by multiple sieving on a 0.8 mm mesh size sieve, until fully combined. Table 2 shows the densities of the explosive compositions selected for the tests. The results show that a decrease in particle size of ammonium nitrate(V) increases the density of the composition. At least two charges were prepared for detonation pressure and velocity measurements.

Table 2. Density of ammonals incl. 10% Al_f

Composition	AN fraction [µm]	Density [g/cm^3]
AN_{R1}	710-400	0.82
AN_{R2}	400-300	0.86
AN_{R3}	300-200	0.86
AN_{R4}	200-100	0.89
AN_{R5}	<100	0.89

2.2. Test methods

2.2.1. Measuring the detonation velocity

The detonation velocity was measured using an ionisation pin probe method with simultaneous measurement of the detonation pressure. Two probes at a distance of 40 mm were installed in the charge shell made of a paper tube with an inner diameter of Φ_w = 38 mm and a wall thickness of 2 mm.

2.2.2. Measuring the detonation pressure

The detonation pressure was measured using manganin piezoresistive gauge. The active part of the sensor is a 25 mm enamelled manganin wire of 0.08 mm diameter. The sensor was connected using a 0.15 mm thick silver-coated copper wire. Figure 3 shows the manganin sensor diagram. A correlation between the change in voltage (as a result of changes in sensor resistance) and the pressure acting on the material is linear and can be expressed as Equation 1:

$$\frac{\Delta V}{V_0} = \frac{\Delta r}{r_0} = \alpha p \tag{1}$$

where: ΔV – change in voltage corresponding to change in resistance Δr, V_0 – initial sensor voltage corresponding to initial resistance r_0, p – pressure, α – piezoresistive coefficient specific for the sensor α = 0.025 GPa^{-1}.

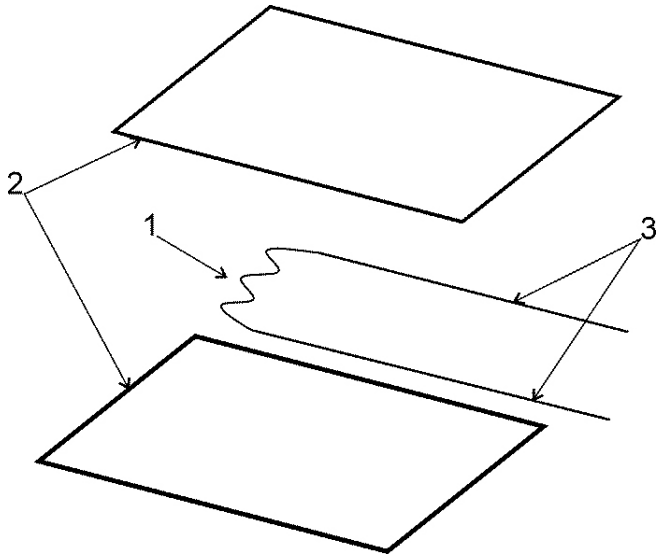
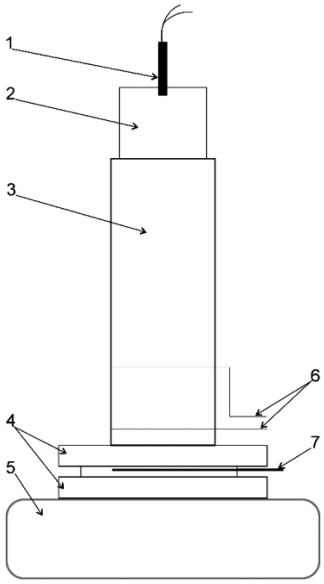


Figure 3. Manganin piezoresistive sensor diagram: 1 – manganin wire, 2 – Teflon® plates, 3 – silver-coated copper wires

2.2.3. Test setup

Figure 4 shows a diagram and photograph of an ammonal charge. The charges were detonated using an ERG electric detonator and an initiator made of 10 g pressed phlegmatized hexogen. Figure 5 shows the schematic of the test configuration. An electrical pulse from the detonator induces a signal actuating the pulse generator which, at a set delay, triggers the QUANTUM COMPOSERS 9730 High Current Pulse Delay Generator which generates a 0.02 to 6 A pulse with an accuracy of up to 1 mA and operates within 0.01 to 100000 Hz at 100 ns resolution.



a)

b)

Figure 4. The velocity and detonation pressure test setup a) test setup diagram: 1 – detonator, 2 – booster, 3 – paper tube, 4 – centring plates, 5 – steel block, 6 – velocity sensors, 7 – pressure sensor; b) photo of a test configuration

From the pulse generator, the current is fed to the piezoresistive sensor, and the voltage drop at the sensor is measured using an oscilloscope. A TEKTRONIX DPO 2024B oscilloscope with a bandwidth of 200 MHz and a sampling frequency of 16 GS/s was used.

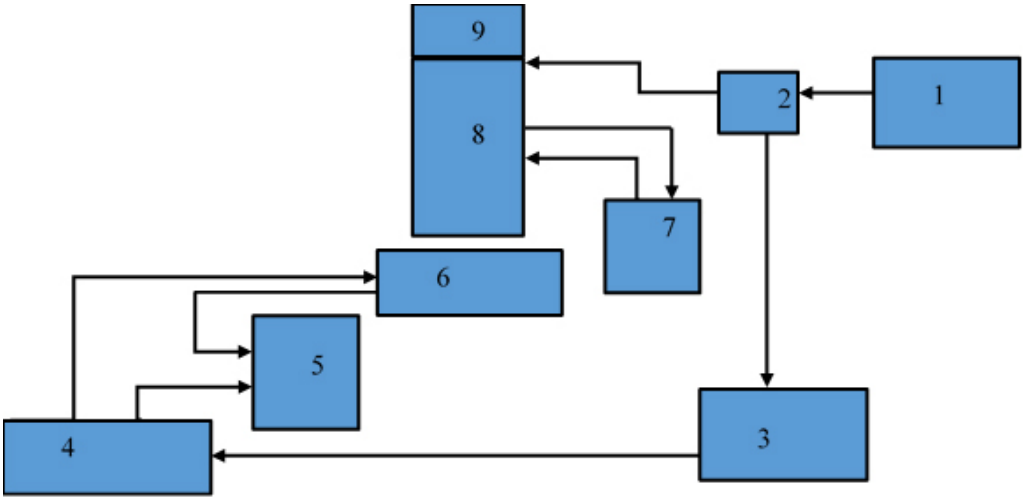


Figure 5. Test setup block diagram: 1 – electric blasting machine, 2 – inductive element, 3 – pulse generator, 4 – switched-mode power supply, 5 – oscilloscope, 6 – detonation pressure sensor, 7 – timer, 8 – ammonal charge with detonation velocity sensors, 9 – detonator

A comparison of the input and output signal from the piezoresistive manganin sensor and the signals recorded as a function of time are the basis for determining the detonation pressure using the obtained curves.

2.2.3. Analysis of the detonation velocity measurement results

The change in voltage in the manganin sensor due to the change in resistance can be used to determine the detonation wave pressure. The absolute difference between the maximum voltage at the peak value corresponding to the shock wave pressure acting on the active element of the sensor and the voltage at the unloaded sensor can be used to determine the detonation pressure. First, the shock wave pressure (p) is calculated from Equation 2 by substituting the equation with the voltage for the unloaded sensor (V_0) and an increase in voltage in the loaded sensor (ΔV). The piezoresistive coefficient α is known and is 0.025 GPa^{-1}.

$$p = \frac{1}{\alpha}\frac{\Delta V}{V_0} \tag{2}$$

The detonation pressure can be determined for the known shock adiabate of Teflon® used as a sensor cover. Based on the correlation between the increase in pressure and the increase in mass velocity (Equation 3) and condition C-J (Equation 4):

$$\Delta p = -(\rho c)_H \Delta u \tag{3}$$

where: $(\rho c)_H$ – wave impedance of the detonation products at CJ; Δp – increase in pressure; Δu – increase in mass velocity;

$$(\rho c)_H = \rho_0 D \tag{4}$$

where: ρ_0 – explosive density; D – detonation velocity

Equation 5, correlating the detonation pressure with the mass velocity at a contact surface between the detonation products and the insulation, can be expressed as follows:

$$p_H - p = \rho_0 D(u - u_H) \tag{5}$$

where: p_H – detonation pressure; p – pressure at the contact surface beween the detonation products and insulation; u_H – mass velocity at the surface CJ; u – mass velocity at the contact surface between the detonation products and insulation.
Based on Equation 5 and the correlation at the detonation wave front: $p_H = \rho_0 D u_H$, the following detonation pressure p_H equation can be formed:

$$p_H = \frac{p+\rho_0 D u}{2} \tag{6}$$

In this equation, the mass velocity u can be determined using a standard shock wave adiabatic curve equation:

$$p = \rho_i(a + \lambda u)u \tag{7}$$

where a and λ are experimentally determined constants.
Using those parameters (a = 1.682 km/s, λ = 1.819 [7]), the equation for the mass velocity u as a function of pressure p can be expressed as:

$$u = 0.462(\sqrt{1.198p + 1} - 1) \tag{8}$$

3. Discussion of the results

3.1. Detonation velocity measurement results

The detonation velocity was measured simultaneously with the detonation pressure. Figure 6 shows the detonation velocity measurement results.

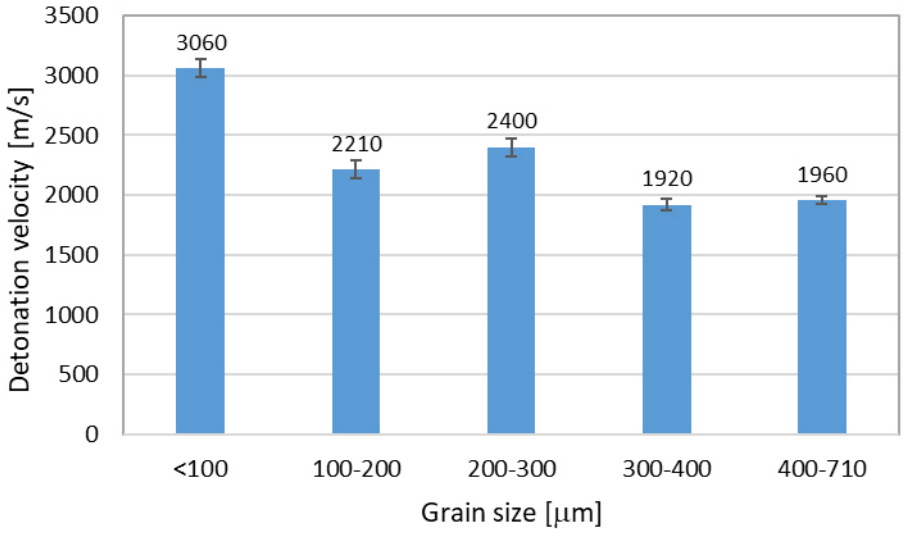


Figure 6. Detonation velocity measurement results for analysed ammonals

Based on the graph, detonation pressure generally increases gradually (with some exceptions) with a decrease in the particle size of ammonium nitrate(V) and reaches its maximum value for the composition containing the finest AN fraction (AN_{R5} composition). Further decreases in AN particle size increases the density of explosive compositions, further increasing the amount of heat generated in per unit volume, and thus, increasing the values of the detonation parameters. A decrease in ammonium nitrate(V) particle size increases the available surface area for the chemical reaction between the oxidiser and fuel.

3.2. Detonation pressure measurement results

Figure 7 shows a typical graph of changes in voltage for a sensor at constant current pulse due to changes in resistance of manganin wire resulting from the shock-wave. Table 3 shows the detonation pressure measurement results.

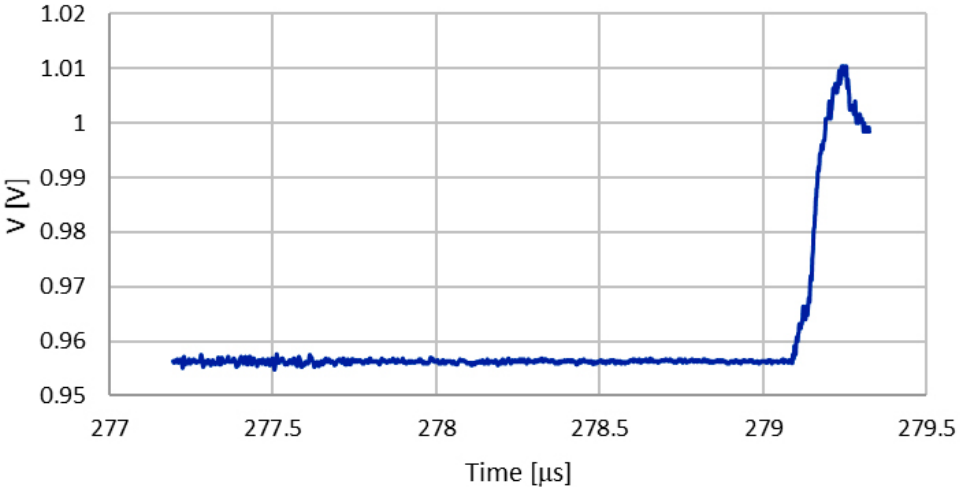


Figure 7. Graph of changes in pressure sensor voltage as a function of time for AN_{R1} ammonal (710-400 µm fraction)

Table 3. Detonation pressure measurement results

No.	Fraction [µm]	ρ [g/cm^3]	D [m/s]	V_0 [V]	V [V]	ΔV [V]	p [GPa]	u [km/s]	p_H [GPa]	$p_{Hśr.}$ [GPa]	Δp_H [GPa]
12	710-400	0.82	1923	0.956	1.008	0.052	2.18	0.415	1.41	1.30	0.11
11		0.82	2011	0.916	0.957	0.041	1.79	0.357	1.19		
7	400-300	0.86	1916	0.817	0.857	0.040	1.96	0.383	1.29	1.42	0.12
8		0.86	1926	0.521	0.551	0.031	2.35	0.440	1.54		
4	300-200	0.86	2427	0.651	0.684	0.033	2.01	0.391	1.41	1.56	0.15
6		0.86	2367	0.640	0.680	0.040	2.48	0.458	1,70		
14	200-100	0.89	2270	0.796	0.829	0.033	1.63	0.332	1.15	1.18	0.03
18		0.89	2092	0.621	0.649	0.028	1.77	0.354	1.21		
22	<100	0.89	3053	0.802	0.831	0.029	1.45	0.302	1.13	1.16	0.03
23		0.89	3072	0.718	0.745	0.027	1.52	0.313	1.19		

The highest detonation pressure was observed for composition AN_{R3}. Initially, with a decrease in particle size of the oxidising agent, an increase in detonation pressure and velocity was observed. However, further decreases in ammonium nitrate(V) particle size and density of ammonal, decreases the detonation

pressure – an interesting correlation which may require further study to determine its nature and cause. One hypothesis which may explain the behaviour of the compositions studied may be that with a decrease in ammonium nitrate(V) particle size, the contact surface area between the oxidising agent and the fuel (Al powder) increases. This may result in a high-intensity reaction of the fuel and the oxidising agent in a wide zone of chemical reactions within the detonation wave, resulting in a large amount of heat being generated. This increase in energy directly affects the detonation velocity. On the other hand, a higher reaction rate of the ammonal components results in a significant decrease in the amount of gaseous detonation products and formation of condensed dialuminium trioxide. This effect can also be accompanied by an increase in the isentropic exponent. The lower amount of gaseous detonation products and the higher isentropic exponent may lead to a decrease in the detonation pressure at smaller ammonium nitrate(V) particle sizes. This hypothesis may require an expanded study program and numerical verifications using advanced thermo-chemical codes.

4. Summary and conclusions

The study allowed a correlation to be made between the density, detonation velocity and detonation pressure of ammonal compositions and the particle size of the ammonium nitrate(V) used. The following conclusions can be drawn based on the results of measurements and related calculations:

- A decrease in particle size of ammonium nitrate(V) used in ammonal compositions increases the density of the analysed explosives.
- A decrease in particle size of ammonium nitrate(V) used in ammonal compositions is accompanied by a tendency to increase the detonation velocity (allowing for measurement uncertainty) of the analysed explosives.
- A maximum detonation pressure was observed for ammonal containing ammonium nitrate(V) with 300-200 μm particle size. This can be due to the amount of aluminium reacting in the chemical reaction zone and changes in the amount of gaseous detonation products and the isentropic exponent value.
- Additional experimental studies to verify the hypothesis correlating the detonation pressure and the particle size of ammonium nitrate(V), are required.

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