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Detonation Parameters of Mixtures Containing Ammonium Nitrate and Aluminium

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Abstract: Ammonium nitrate (AN) is the most popular ingredient of commercial explosives. Pure AN is not treated as an explosive compound but a slight organic or inorganic addition makes the mixture capable of explosion. In the paper the experimental tests were focused on aluminium (Al) as the most effective sensitizer. Mixture of AN or water solution AN with aluminium (ammonals and hydro-ammonals) were studied. Using electromagnetic method of measuring of the mass velocity behind the detonation wave front (Dremin's method), detonation parameters as well the shape of detonation waves in explosive mixtures were determined. The essential factor influencing the detonation parameters of the studied explosives is their physical structure.

Keywords: ammonium nitrate based mixtures, detonation parameters, Dremin's method

Introduction

Ammonium nitrate (AN) is the basic ingredient of commercial explosives such as ANFO mixtures, ammonites, dynamites, ammonals, slurry blasting agents and emulsion-type explosives, commonly used in mining industry. The main features which determine the wide-range use of AN for producing mining explosives are the relatively low price and very easy access as well as a high capability of oxidizing different organic and inorganic substances in the conditions of high-rate explosive process. Pure AN (prilled or crystalline) is not considered an explosive substance but an effective oxidiser. Still, international rules regard AN containing more than 0.2% of organic

additives as a dangerous material capable of explosion (Class 1 according to UN regulations).

The quantity of AN and other inorganic nitrates in blasting compositions used in mining industry as a rule exceeds the level of 60-70% by weight, with up to 95% in ANFO mixtures. Thus, the above mentioned various types of AN-based explosive mixtures rely on different ideas to increase the AN detonation ability. The most ready method to increase the AN detonation ability is to add some high brisance explosive, such as trinitrotoluene (TNT) or nitro-glycerine. Such explosive additives amounting to more than 10% make AN capable of detonation in small diameter charges: 20 mm or less. The addition of organic substances, especially liquid hydro-carbonates, causes the critical diameter of the mixture (ANFO) to decrease to 50-60 mm. High porosity of AN granules is the basic condition for producing relatively sensitive and powerful ANFO mixtures [1].

Aluminium powder has been revealed as the most effective sensitizer of ammonium nitrate based explosive compositions. In the paper [2], flaked, fine grade Al was used for manufacturing powdered, low detonation velocity high explosives for cladding metal plates. An addition of several percent of flaked aluminium also imparts explosive properties to water based AN solutions, especially concentrated ones [3, 4].

This paper provides a study of the detonation properties of AN and Al mixtures (ammonals) as well as water based saturated AN solution and Al mixtures (slurry blasting agents or hydro-ammonals). By using the electromagnetic method developed by prof. Dremin, the nature of detonation development in the explosive AN-Al mixtures was revealed, both in loose ammonals and in liquid hydro-ammonals.

Aluminium as ammonium nitrate sensibilizer

AN is a substance with relatively weak explosive properties and is not considered an explosive in many classifications. However, some grave industrial disasters caused by exploding AN show that the hazard should not be underestimated [5].

Adding some combustible material, such as nitro compounds, liquid hydrocarbons or metal powders to AN increases significantly its explosibility. Still, the most effective sensibilizer of ammonium nitrate turns out to be disintegrated aluminium. Since ammonals characterize the high ability to detonation, they were used successfully for explosive welding of large surface

area sheet metal and could be prepared on site with a simple technology [6]. A study of the explosive properties of AN mixtures with an addition of aluminium is presented in paper [7].

A comparison of the sensitizing properties of flaked aluminium and small crystalline TNT with respect to ammonium nitrate is presented in Figure 1 which shows the function of the critical diameter of the tested two-component mixtures against the combustible ingredient content. The disintegration of ingredients in the ammonite (a mixture of TNT and AN) was below 0.4 mm. The ammonal consisted of AN with a grain size below 0.2 mm while flaked aluminium powder (with a covering power of 4000 cm^2/g) was used as sensibilizer. The density of the tested mixtures was 0.75-0.85 g/cm^3 [8].

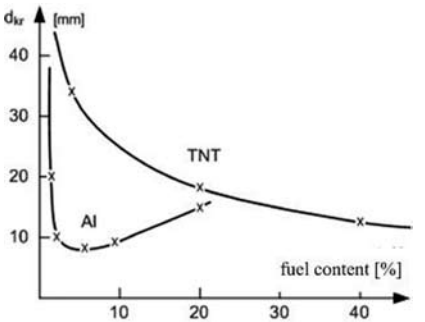

Figure 1. Dependence of critical diameter of AN mixtures vs. a fuel content.

As seen in the diagram in Figure 1, TNT is a far less effective sensibilizer of ammonium nitrate compared to very fine aluminium powder. The explosive properties of ammonal (a critical diameter below 20 mm) are clearly visible with an aluminium content less than 1% while in the case of ammonites with TNT, they are not visible until the TNT content reaches about 20%. In contrast, the industrial grade ammonites sensitized with very sensitive nitroglycerine show similar explosive properties with a nitroglycerine content of 4-6%.

Experimental

Dremin's method for the measurement of mass velocity of detonation waves

Due to the high ability to detonation of ammonals as verified in experiments (low critical diameter value and sensitivity to initiation by blasting cap), an

electromagnetic method was used for the measurement of detonation parameters. The development of the theoretical basis and measurement methodology is the merit of the team headed by prof. A.N. Dremin [9-11]. The author hereof implemented the electromagnetic method into the research practice at the Military University of Technology in Warsaw [12-14].

The essence of the method consists in measuring the electromotive force (E) generated at the tips of a conductor of a length (l), moving at the velocity (u), in the magnetic field with induction (B). As is known, the quantities mentioned are interrelated by the following formula:

$$\vec{E} = \left[\vec{B} \times \vec{u}\right] \cdot l$$

In the case of a stationary detonation process, the measurement by electromagnetic method of the mass velocity (u), detonation velocity (D) and the chemical reaction time (τ) makes it possible to determine further parameters of the detonation wave: the pressure (p), the width of the chemical reaction zone (a) and the polytropic exponent of the detonation products (n). The Dremin's method enables to record mass velocity profiles both for ideal and non-ideal detonation regime as well.

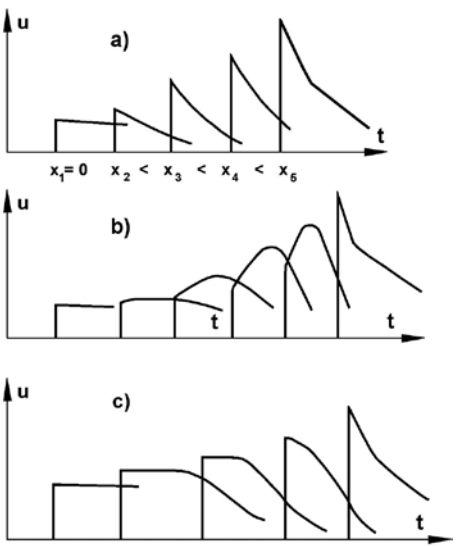

Figure 2. Profiles of a mass velocity during development of detonation in heterogeneous explosives [11]; TNT of density 0.9 g/cm^3 (a), pressed TNT of density 1.6 g/cm^3 (b), casted TNT of density 1.6 g/cm^3 (c).

Using the electromagnetic method for the measurement of mass velocity enables observation of the detonation wave development process by placing the measurement sensors at various distances from the point where the initiating shock wave enters the tested explosive.

Using the electromagnetic method, Dremin and others described the nature of the detonation developing in liquid explosives and in solid explosives of various physical aspect: loose, pressed and cast [11]. The new measurement technique applied by Dremin and others made it possible to define the character of detonation development both quantity and quality wise depending on the physical aspect of the explosive. For homogeneous (liquid) explosives, a two-phase, stepwise nature of detonation initiation was revealed. For non-homogeneous explosives, three possible variants of monotonic transition of initiating shock wave to stationary detonation wave were distinguished (Figure 2).

The influence of the fineness of ingredients on the explosive parameters of mixtures containing ammonium nitrate and aluminium

As the first step, detonation parameters of AN and Al mixtures have been studied while changing the fineness of ingredients. Crystals of pure AN were milled, dried at 353 K (80 °C) to the humidity of less than 0.5% and sieved into the respective fractions. Two different Al products have been chosen as a fuel for the explosive mixtures. Fine flaked aluminium dust, with 86% of pure Al and 1% of stearic acid as hydrophobic agent, has the specific surface of 4500 cm^2/g. Second type Al was powder containing 98% of Al with particle size less than 0.2 mm. The experimental mixtures were prepared by mechanical agitation just before filling the confinements (paper or thin-wall plastic tubes).

Table 1. Detonation parameters of ammonals

No.	Content [%]		Content NH_4NO_3 [%] fraction [mm]			Density ρ_o [kg/dm^3]	Critical diameter d_{kr} [mm]	Detonation velocity D [km/s]	Mass velocity u_f [km/s]	Detonation pressure p_f [GPa]
	Dust Al	Powder Al	< 0.2	0.2-0.5	0.5- 2.5					
1	5	-	95	-	-	0.85	**7**	3.30	1.0	2.8
2	5	-	-	95	-	0.85	**12**	2.55	0.9	2.0
3	-	5	-	95	-	0.95	**25**	2.1	0.75	1.5
4	2	-	98	-	-	0.85	**8**	2.7	1.0	2.3
5	2	-	-	98	-	0.80	**15**	2.1	0.7	1.2
6	2	-	-	-	98	0.9	**40**	1.3	0.4	0.5
7	1	-	99	-	-	0.90	**14**	2.05	0.50	0.9

The dependence of the critical diameter and detonation velocity of ammonals as the function of the aluminium content of those mixtures was studied in the paper [7]. High effectiveness of aluminium in increasing the detonation ability of AN can be observed already for the Al content below 1% by weight [8]. The detonation parameters of ammonals were determined using electromagnetic method of measuring mass velocity behind the shock wave front. Charges for experiments were prepared in plastic pipes $Ø_{int.}/Ø_{ext.}$ = 45/50 mm. Physical and detonation parameters of ammonals containing different types of Al and the size of AN crystals are presented in Table 1.

The influence of the particle size of AN and Al on the shape of detonation impulse can be observed in the mass velocity records for ammonal containing 5% Al (Figure 3). In the next series of records, one can compare detonation impulse for ammonal containing 2% Al and different fractions of AN (Figure 4). The transition of the initial shock wave to detonation wave was also studied for ammonal containing 2% Al (sample no. 4 from Table 1). The mass velocity shapes recorded for various distances (x) show the development of the detonation wave in the charge of ammonal (Figure 5). The pressure of the initial shock wave passing into the charge (x = 0 mm) was relatively low – 0.7 GPa.

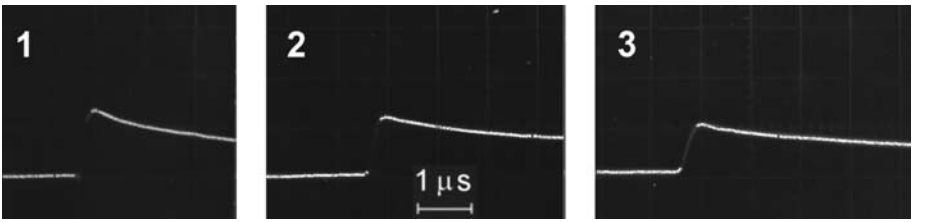

Figure 3. Mass velocity records of ammonals (sample 1, 2 and 3 – respectively to Table 1).

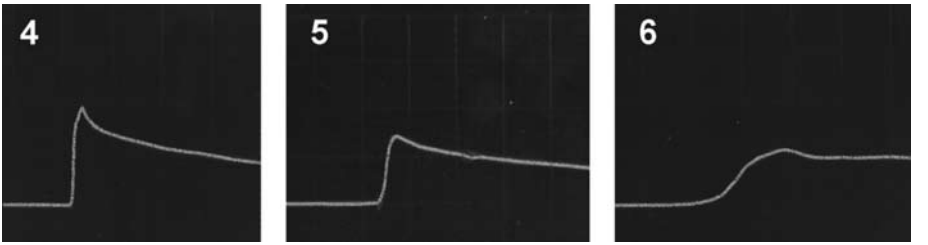

Figure 4. Mass velocity records of ammonals (sample 4, 5 and 6 – respectively to Table 1).

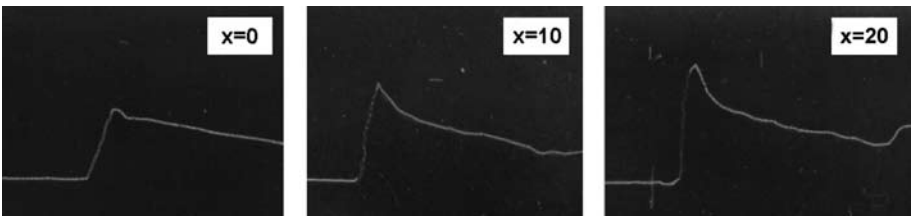

Figure 5. Mass velocity records illustrating the development of the detonation wave in the charge of ammonal (x – distance in the charge in mm).

Explosive parameters of mixtures containing saturated AN solutions and aluminium

In order to obtain hydro-ammonal with a high detonation sensitivity, saturated water AN solution of high viscosity should be mixed with hydrofobized flaked aluminium powder (or dust). It has been revealed that mixtures with high detonation ability can be obtained for an Al content of minimum 3% [3]. Below that limit, the mixture parameters are not repeatable. The physical and detonation parameters of the studied hydro-ammonals are presented in Table 2. The hydro-ammonals prepared for experiments consisted of 20% of water; 4, 6, 8, 10% of Al and the rest was AN (mostly dissolved in water, minor part as a solid phase) with 0.5% of guar-gum as a thickening agent.

Table 2. Detonation parameters of hydro-ammonals

Content of Al [%]	Density ρ_o [kg/dm^3]	Critical diameter d_{kr} [mm]	Detonation velocity D [km/s]	Mass velocity u_1 [km/s]	Detonation pressure p_1 [GPa]	Chemical reaction time τ_1 [μs]
4	1.24	8	3.16	0.54	2.1	1.05
6	1.23	7	3.70	0.70	3.2	0.8
8	1.20	6	3.80	0.75	3.4	0.66
10	1.17	6	3.85	0.77	3.5	0.60

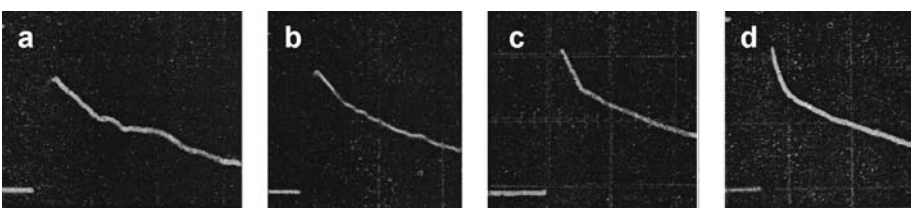

Figure 6. Mass velocity records of hydro-ammonals containing 4, 6, 8 and 10% of flaked aluminium (a – d) respectively.

The experiments with hydro-ammonals were carried out using charges confined in plastic tubes $\Phi_{int.}/\Phi_{ext.}$ = 36/42 mm. Records of mass velocity for mixture with 4, 6, 8 and 10% of Al are presented in Figure 6. Similarly as for ammonals, series of tests were performed to reveal the character of detonation wave development in hydro-ammonals. The shapes of mass velocity in hydro-ammonal containing 8% of Al at different distances in tested charges are presented in the records (Figure 7).

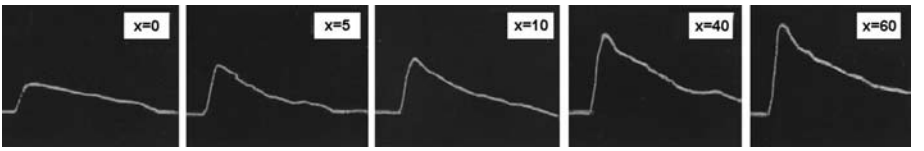

Figure 7. Mass velocity records illustrating the development of the detonation wave in the charge of hydro-ammonal with 8% of flaked aluminium (x – distance in the charge in mm).

Conclusions

The results of experimental tests enabled comparison of the effectiveness of aluminium powder as a sensitizer of ammonium nitrate and its saturated water solution. Ammonals of sufficient sensitivity can be obtained with about 1% of Al powder in the mixture. A similar sensitivity in the case of hydro-ammonals, can be observed with a higher content of Al in the mixture, i.e. above 3%. One should note that in the saturated solution of AN, the inert ingredient (water) occupied about one third of total weight. These results show that flaked aluminium is the most effective substance for increasing detonation ability of AN based explosives.

The essential factor influencing the detonation parameters of the AN–Al mixtures is the physical structure of the studied explosives. For ammonal, the main physical factor influencing the detonation parameters is the size (dimensions) of Al particles and AN grains as well. The observed feature enables forming the detonation pressure impulse in a wide range of parameters. It can be useful e.g. for rock mining or for the cladding of metals. In the case of hydro-ammonals, the main influence is exercised by such elements of the physical structure as the content of the gas phase (air bubbles) and the interrelationship among the Al particles, gas bubbles and the AN solution [3, 16]. The possibility of the detonation pressure impulse formation in that case is not as wide as for ammonal. Since the density of hydro-ammonals is significantly higher, detonation parameters are proportionally greater.

It should be emphasized that the critical diameter of both ammonals and hydro-ammonals is very small. The minimal value of this parameter is 6-8 mm. This proves very high thermochemical efficiency of the initiation mechanisms which cause the chemical reaction between AN and Al. The tests made to determine the character of detonation wave development revealed the similarity, in spite of many differences, of the physical structure of ammonal and hydro-ammonal. The character of detonation waves development in the mixtures under study is the same as for high explosives of low density [11]. The critical pressure of initiation for ammonals and hydro-ammonals is comparable, in spite of the fact that hydro-ammonals contain about 20% of thermochemically inert water. As the factor responsible for the high sensitivity of the explosives mixtures, one should point out the gas phase which occupies minimum 15% of the volume. The gas phase, distributed as air bubbles (in hydro-ammonal) or hollow space (in ammonal), plays the fundamental role in the initiation of fast chemical reactions according to the hot spots theory [15].

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