

DETONATION PROPERTIES OF EXPLOSIVES CONTAINING NANOMETRIC ALUMINUM POWDER

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Nanometric aluminum powder is known to react more rapidly than conventional, micron-size aluminum grades in propellant and explosive compositions. Defence Research and Development Canada - Valcartier (DRDC-V) and the Defence Science and Technology Organisation (DSTO) are collaborating to assess the potential of nanometric aluminum powders in explosive compositions. Various plastic-bonded explosives (PBXs) and TNT-based formulations have been developed to compare ultrafine and conventional micron-sized aluminum. Explosive performance was determined by VoD measurements and plate dent depth tests. The study was also complemented by air-blast tests to evaluate the difference in energy release in the far-field. It was found that for PBX compositions, no significant differences were observed between formulations containing micron-sized and nanometric aluminum. For mixes of TNT and aluminum, an improvement was noted in the velocity of detonation and in plate dent depths using ultrafine aluminum. Aquarium tests were run on TNT/Al blends to confirm the improvement observed, to evaluate the relative performance of the different sizes of aluminum and to qualify the behaviour of the aluminum in such an explosive.

INTRODUCTION

Aluminum powder is a common ingredient in energetic materials. The aluminum is used to increase the energy and raise the flame temperature in rocket propellants. It is also incorporated in explosives to enhance air blast, increase bubble energies in underwater weapons, raise reaction temperatures and create incendiary effects. In explosives, it is generally assumed that combustion of aluminum particles occurs behind the reaction front (during the expansion of the gaseous detonation

products), so that the particles do not participate in the reaction zone, but rather act as inert ingredients.

Nanometric aluminum has recently become available in quantities large enough for introduction into energetic materials and small-scale performance testing. The most widely known product is the ultrafine aluminum powder "Alex[®]", sold by the Argonide Corporation. Alex comprises spherical particles having a diameter of 100-200 nm. The powder exhibits unusual thermal behaviour¹⁻⁶ that was originally associated with "stored energy"¹ due to defects in the crystal lattice. As this additional

energy could contribute to explosives performance, the concept of “stored energy” has created high expectations for these powders in energetic materials. Subsequent research, however, demonstrated that any such stored energy in the aluminum nanopowders^{2-4,7}, if it occurs, is short-lived. The liberation of energy at low temperatures is due instead to oxidation of the extremely small particles. Contradictory information was then published on other types of aluminum nano-powders⁶.

A lot of work has been accomplished recently with nanopowders in energetic materials. For example, it has been proven that because of their large surface area, the nanopowders can increase the burn rate in some types of propellants^{1,3,8-10}. There were also significant developments made in the “super thermite” area with mixes of nanometric aluminum and metal oxides¹¹. Those compounds are said to react at rates approaching (and under particular conditions even equivalent to) those of high explosives.

In explosives, it is not clear if the nanoparticles are small enough to react faster than micrometric particles and, therefore, to participate in the detonation reaction zone. There have been early claims of improvements using nanopowders in explosives^{1,12}. Other researchers subsequently have demonstrated some improvements in the velocity of detonation (VoD) of ADN/Al blends using nanometric aluminum¹³. Tulis *et al.*¹⁴ also measured an increase in the VoD of fuel-oxidizer blends (lactose-aluminum-ammonium perchlorate) when Alex was compared to aluminum flakes. However, there were other reports where nanometric aluminum showed either no improvement of performance or even a decrease of performance¹⁵⁻¹⁸.

The reaction mechanism of nanometric aluminum in explosives is as yet unclear. Many researchers have reported on a large number of different compositions with mixed results. The objective of the current paper is to study the effect of nanometric aluminum in explosives. This data on the effects of nanometric aluminum in simple explosive compositions will help to determine if the detonation

properties can be enhanced using very small aluminum particles.

EXPERIMENTAL

a) Aluminum powders

The nanometric aluminum chosen for the experimental study was Alex[®] from Argonide Corporation, in Florida, USA. The particle size was between 100-200 nm. The reference micrometric aluminum used by DRDC-V for this study was Valimet H-15, with an average particle size of 12 μm . Valimet H-2 (spherical, 2 μm) and MDX-75 from Alcan (spherical, 21 μm) were also included in some formulations when different types of Al were necessary. The reference aluminum used by DSTO was Cap45a from Comalco Aluminium Powders (17 μm).

b) Explosive formulations

Three distinct types of explosives were tested: cast-cured plastic-bonded explosives, TNT-based melt-cast explosives and an Ammonium Nitrate Fuel Oil (ANFO) formulation.

The plastic-bonded explosives (PBXs) were selected to complement and confirm the results presented by Cliff *et al.*¹⁷ on HPTB/RDX/Al PBXs. The compositions were mixtures of HTPB, HMX and aluminum. Furthermore, it was hypothesized that the close contact of aluminum and of an energetic component, such as TNT, could enhance the reaction rate of Al with the reaction products. For this reason, mixtures containing an energetic binder system were also selected for evaluation. The PBX formulations are presented in Table 1. Cylinders of 25.4 and 38.1 mm in diameter by 228 mm long were cast.

For the ANFO formulations, crushed Ammonium Nitrate was sieved (150 mesh or 105 μm) and the passing fraction was blended with fuel oil and 10% of aluminum (either Alex or H-15). The final blend was oxygen balanced by adjusting the fuel oil. The final composition was 87.5% AN, 2.5% fuel oil and 10% aluminum. Microballoons (2-5%) were added to adjust the final explosive density and increase the sensitivity.

TABLE 1. COMPOSITION OF THE PLASTIC-BONDED EXPLOSIVES

Ingredient	PBXI-1	PBXI-2	PBXI-3	PBXI-4	PBXE-1	PBXE-2
HTPB	9.6 %	9.6 %	9.6 %	9.6 %	-	-
DOA	5.6 %	5.6 %	5.6 %	5.6 %	-	-
GAP	-	-	-	-	11.1 %	11.1 %
TEGDN/TMETN	-	-	-	-	11.1 %	11.1 %
TDI	0.8 %	0.8 %	0.8 %	0.8 %	-	-
IPDI/N-100	-	-	-	-	1.7 %	1.7 %
Stabilizer/catalyst	-	-	-	-	0.1 %	0.1 %
HMX	74 %	74 %	64 %	64 %	-	-
RDX	-	-	-	-	66 %	66 %
Al H-15	10 %	-	20 %	-	10 %	-
Al Alex	-	10 %	-	20 %	-	10%

(HTPB = Hydroxyl-terminated Polybutadiene, DOA = Di-Octyl Adipate, GAP = Glycidyl Azide Polymer, TEGDN = Triethyleneglycol Dinitrate, TMETN = Trimethylol Ethane Trinitrate, IPDI = Isophorone Diisocyanate, N-100 = Desmodur N-100).

c) Testing

The performance of the explosives was assessed by measuring the VoD, the heat of detonation, plate dent depths, the pressure and impulse in air-blast tests, as well as the performance in aquarium tests. The VoD was measured using ionisation probes for the PBXs and the TNT-based explosives. The explosives were initiated by a Reynolds RP-83 detonator coupled with a 31.8 mm diameter by 15.2 mm long RDX/wax booster. A length of at least two diameters was left at the top of the cylinders to allow for the development of the detonation wave. The charges were fired in the upright position and a steel witness plate was placed underneath the explosive cylinders to confirm a full-order detonation. All the charges were tested unconfined, except for the ANFO charges. The velocity of the ANFO charges was measured using a continuous resistance wire and they were fired inside 25.4 mm diameter by 610 mm long schedule 40 steel tubes.

The heat of detonation was evaluated using a detonation bomb calorimeter developed for DRDC-V¹⁹. The detonation calorimeter was seen as an effective way of measuring any additional “stored energy” liberated by the aluminum during an actual detonation. The details of the apparatus have been previously described^{18,20,21}.

The air-blast tests were performed on spherical charges. The cast compositions were spheres of 592 cm³, while the ANFO blends were placed in glass spheres of 1555 cm³ in volume. All charges were designed to be about 1 kg in mass. They were suspended 3.05 m above the ground and PCB free-field blast pressure probes were located at 1.25 m, 1.5 m, 2.0 m and 2.5 m. Four charges of each composition were fired and the average was reported.

DSTO performed aquarium tests on cylindrical charges of Tritonal variants, 25.4 and 50.8mm in diameter and 200mm long. The charges were boosted with right cylinders of Pentolite of matching diameter, and initiated with RISI 501 EBW detonators. Charge assemblies were immersed horizontally in a 40cm × 40cm × 60cm water-filled aquarium. The back of the aquarium was marked with a 50mm × 50mm reference grid, and fitted with two PF-300 flash bulbs and a light diffuser to illuminate the water shock wave. The underwater detonation was photographed by a Hadland Imacon 468 CCD camera, resulting in seven frame images and one streak image. The camera exposures were generally timed to take four images of the detonation front travelling through the charge, and three images of the expanding bubble. Streak images were generally taken with a duration of 60 μs, using a slit width of 100 μm.

MREL performed combination cylinder/aquarium tests under contract from DRDC-V. The explosives were TNT/Al 80/20 (Tritonal-type) charges 25.4 and 50.8 mm in diameter and 150 mm long. All streak photographs were recorded using a CORDIN Model 194 continuous writing streak camera, having a mirror period of 900 μ s. The camera slit was located 7.5 cm from the initiated end of the charge. A typical trial would involve initiation of a 30 cm diameter by 92 cm long tube filled with argon to illuminate the charge. An example of a streak record is presented in Figure 1. Both sides of the charge (top and bottom) were recorded and analysed. The shape at the end of the charge was not recorded.

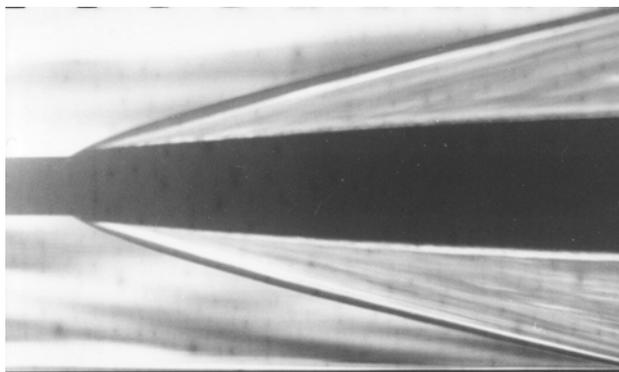


FIGURE 1. STREAK RECORD FROM AN AQUARIUM TEST

Some critical diameter tests were run on TNT/Al formulations only. Cylinders of 160 mm in length and of various diameters were initiated vertically by an RDX/wax booster pellet (31.8 mm diameter by 15.2 mm long). A 3.2-mm thick steel witness plate was placed at the bottom, separated from the explosive cylinder by a 0.3-mm cardboard spacer to avoid reflections of the shock wave. Two tests were run at each diameter. To complement those tests, conical cylinders were fired. The charges were 25 mm in diameter at the top, 10 mm in diameter at the bottom and they were 305 mm long. They were fired in an upright position. A 3.2-mm thick steel witness plate was placed at the bottom and a 4.8-mm thick one was positioned on the side of the charge. The detonation was recorded on a Cordin model 150A streak camera.

RESULTS AND DISCUSSION

a) VoD and Heat Calorimetry

The results for the PBX compositions are presented in Table 2, and are grouped by charge diameter because the compositions were fired unconfined and below the diameter at which the measured detonation velocity reaches a steady-state (D_∞). The addition of Alex has very little effect on the detonation velocity of the PBXs. This is consistent with the results from other sources on RDX- and AP-based PBXs¹⁷. The energetic formulations were especially surprising, due to the significant decrease observed in the VoD for these compositions. It is unclear whether this decrease in performance is related to the processing difficulties with Alex, to the lower Al content of Alex (Alex typically contains 85-88 % active Al while conventional powders contain generally > 99%²²), or to other reaction mechanisms.

TABLE 2. PERFORMANCE OF THE PLASTIC-BONDED EXPLOSIVES

Mix	Density (g/cm ³)	Diameter of the charge (mm)	Detonation velocity (m/s)	Heat of Detonation (kJ/kg)
PBXI-1	1.67	25.4	7748	-
PBXI-2 (Alex)	1.66	25.4	7748	-
PBXI-1	1.67	38.1	7838	-
PBXI-2 (Alex)	1.66	38.1	7804	-
PBXI-3	1.72	25.4	7450	4632
PBXI-4 (Alex)	1.73	25.4	7473	4661
PBXI-3	1.71	38.1	7606	-
PBXI-4 (Alex)	1.72	38.1	7586	-
PBXE-1	1.70	25.4	7724	-
PBXE-2 (Alex)	1.69	25.4	7494	-
PBXE-1	1.70	38.1	7785	-
PBXE-2 (Alex)	1.67	38.1	7465	-

For the mixtures of Alex and Composition B, presented in Table 3, the results are similar to those observed for the inert PBXs. In this case, four different types of aluminum were tested. A small decrease in VoD was observed with smaller particle sizes. The difference between the detonation velocities of Comp. B/H-15 and Comp. B/Alex was

small (< 2 %). However, there appears to be a trend of decreasing velocity with the diameter of the Al particles. Conversely, the heat of detonation shows a reverse trend (2% increase from H-15 to Alex). This trend may indicate that the smaller the Al particle size, the more Al that reacts in the system and contributes to the detonation energy^{20,21}. This reaction may occur rapidly enough behind the detonation front that the performance of these explosives is affected in the detonation calorimeter configuration.

TABLE 3. PERFORMANCE OF COMPOSITION B AND ANFO MIXES

Mix Type	Al (%)	Al Type	Density (g/cm ³)	Detonation Velocity (m/s)	Heat of Detonation (kJ/kg)
Comp. B/Al	10	MDX-75	1.74	7740	5621
Comp. B/Al	10	H-15	1.74	7744	5816
Comp. B/Al	10	H-2	1.74	7680	6004
Comp. B/Al	10	Alex	1.74	7598	5927
Comp. B	0	-	1.69	7891	5389
ANFO/Al	10	H-15	0.90	3639 ^(a)	5856
ANFO/Al	10	Alex	0.90	3605 ^(a)	5991

(a) Confined in schedule 40 steel pipes

For ANFO mixes with aluminum, a small decrease in VoD was observed with Alex, and an increase of the heat of detonation was measured as well. The ANFO explosives were selected for their balanced oxygen content (all other mixtures studied were oxygen-deficient). It was thought that, at these small particle sizes, the Al particles would be strong oxygen scavengers. The oxygen balance did not help to improve the performance.

The mixtures with only TNT and aluminum were those that exhibited the largest changes with aluminum type. Three percentages of Al were studied, 10 %, 20% and 30 %. The performance results are presented in Table 4, and are grouped by charge diameter. The charges with Alex always showed higher VoDs than the charges with H-15 (micrometric). The difference in performance is larger at small charge diameters. The difference decreases as the diameter increases, and it seems obvious that this difference will be eliminated at

larger diameters. Some charges may have exhibited borderline detonation, and one of the charges with MDX-75 at TNT/Al 70/30 did not detonate. All these charges are close to the critical diameter. Cast TNT has a reported critical diameter of 27.4 mm²³. All the charges were then close to the critical diameter, and below D_{∞} .

TABLE 4. PERFORMANCE OF TNT/AL MIXES

Al (%)	Al Type	Density (g/cm ³)	Diameter of the charge (mm)	Detonation Velocity (m/s)	Heat of Detonation (kJ/kg)
10	H-15	1.67	25.4	5718	5307
10	Alex	1.67	25.4	6508	5479
10	H-15	1.64	31.8	6554	-
10	Alex	1.68	31.8	6638	-
20	H-15	1.74	25.4	6182	-
20	Alex	1.74	25.4	6598	-
20	H-15	1.72	31.8	6456	-
20	Alex	1.74	31.8	6724	-
30	MDX-75	1.82	25.4	5740	6184
30	H-15	1.82	25.4	6228	6519
30	H-2	1.82	25.4	6483	6660
30	Alex	1.82	25.4	6628	6749
30	MDX-75	1.80	31.8	6400	-
30	H-15	1.80	31.8	6428	-
30	H-2	1.82	31.8	6707	-
30	Alex	1.84	31.8	6708	-
30	H-15	1.81	57.8	6591	-
30	Alex	1.84	57.8	6742	-

Table 4 demonstrates clearly that the particle size of aluminum affects the performance of TNT/Al compositions. The smaller aluminum particles produce a higher VoD in unconfined charges. At 31.8 mm diameter, the mixtures with H-2 aluminum (2 μm) gave a VoD as high as those with Alex aluminum. The increase of performance is therefore not limited to nanometric aluminum.

The enhancement from nanometric aluminum (vs micrometric aluminum) in such mixtures has been previously reported^{17,18,24}. Dorsett *et al.*²⁴ have noted increases in the brisance from plate dent tests in TNT/Alex and TNT/RDX/Alex blends. Figure 2

presents the observed increases from plate dent tests. Dent tests can be correlated to the detonation pressure of explosives²⁵, with these results indicating improvements to the P_{CJ} of the compositions at small charge diameters. DSTO is currently testing charges of larger diameters to determine if the enhancements are generic or specific to the diameter range so far assessed.

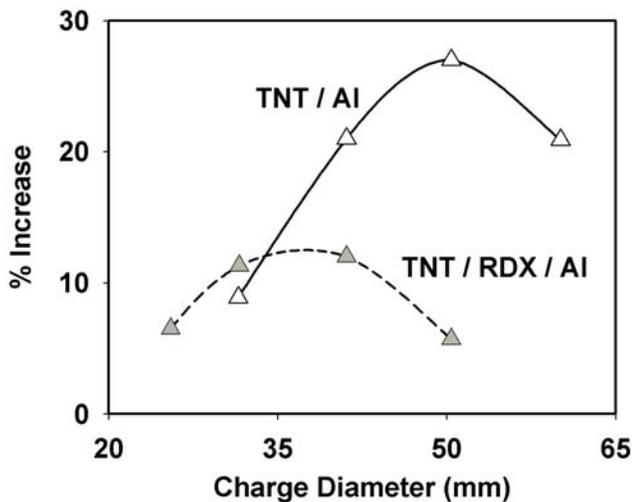


FIGURE 2. OBSERVED INCREASES IN PLATE DENT DEPTHS OF TNT/AL AND TNT/RDX/AL FORMULATIONS CONTAINING ALEX.

b) Aquarium tests

Aquarium tests are typically used to study underwater detonations, particularly early-time formation of the water shock wave and the gas bubble of detonation products. Because the water acts to contain the detonation products, the detonation front within the solid explosive can be easily differentiated from the expanding products. For aluminum is also readily apparent. Dorsett *et al.*²⁴ demonstrated through streak and frame images (Figures 3 and 4) during aquarium tests that Alex reacted earlier and faster than 17 μm aluminum in Tritonal-type formulations (peak at 8 μs lasting for 17 μs compared to appearance of light at 25 μs lasting for more than 100 μs). This early reaction may explain the increased brisance reported, as well as the larger heat of detonation measured in this study.

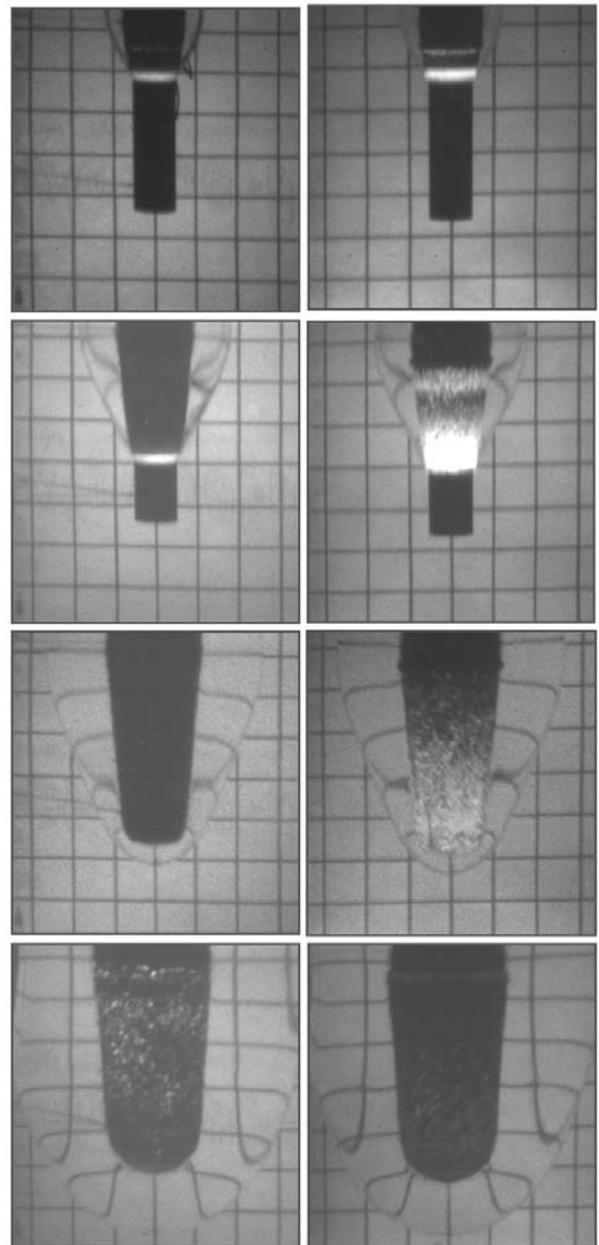


FIGURE 3. FRAME PHOTOGRAPHS FROM DSTO UNDERWATER DETONATIONS OF TRITONAL CHARGES WITH CAP45A (LEFT) AND ALEX (RIGHT). PHOTOGRAPHS TAKEN APPROXIMATELY AT 18 μs , 31 μs , 50 μs AND 82 μs (TOP TO BOTTOM).

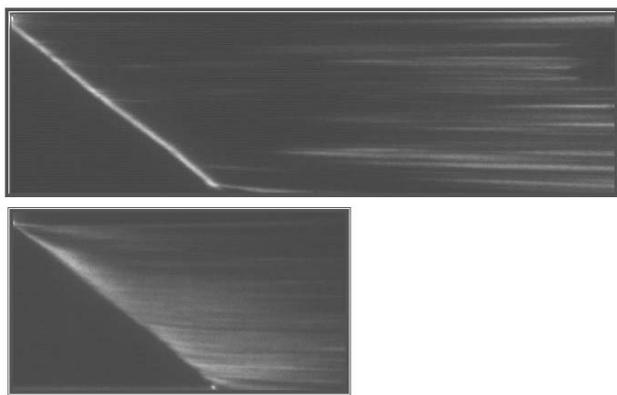


FIGURE 4. STREAK IMAGES OF UNDERWATER DETONATION OF TRITONAL CHARGES MADE WITH CAP45A (TOP, SWEEP TIME 85 μ S) AND ALEX (BOTTOM, SWEEP TIME 45 μ S).

The aquarium tests performed at MREL on Tritonal-type formulations (TNT/Al 80/20) did not reveal large differences between micrometric and nanometric aluminum. Typical shock and expansion histories are shown in Figure 5. Anderson and Katsabanis²⁶ showed that the pressures calculated from the initial shock velocities are lower for the charges with Alex. They also demonstrated that the expansion of the detonation products is somewhat faster for the Alex-based charges. One simple method to evaluate the explosives is to compare the shock and gas expansion radii at a given time²⁷. The comparison at 10 μ s for the average of all the firings is presented in Table 5. The shock radii are equal or lower for Alex, while the expansion of the gases is faster. This correlates well to the faster reaction of the Alex demonstrated in Australia and may explain the small differences in plate dent tests. The partial confinement provided by the water may explain the absence of improvement in the aquarium tests. The confinement may also be the cause of the absence of improvement measured in cylinder tests by Baudin *et al.*¹⁵.

c) Critical diameter tests

The results of tests with TNT/Al mixtures indicate that replacement of conventional aluminum with Alex reduces the critical diameter of Tritonal-type formulations (TNT/Al 80/20) by *nearly a factor of two*. In one set of tests, long conical charges were fired from the base, and the detonation front tracked by a witness plate placed on the side of the charge, and a streak camera aligned on the axis. Detonation

failure occurred in the H-15 charges at conical diameters of 14.0 and 13.5 mm respectively, whereas detonation was sustained the entire length of the Alex charges, suggesting a critical diameter smaller than 10 mm. A second method involved firing right-circular cylinders of various diameters (Table 6). For H-15 aluminum, the charges detonated at 20 mm and failed at 15 mm. This is consistent with the data on critical diameter from the literature for Tritonal (18.3 mm)²⁸. This is also in agreement with the results from the previous tests, given that the conical charges were probably overdriven from the wider-diameter base. For TNT/Alex, the charges detonated at 10 mm, which again indicates a critical diameter smaller than 10 mm, which is nearly half that of conventional Tritonal.

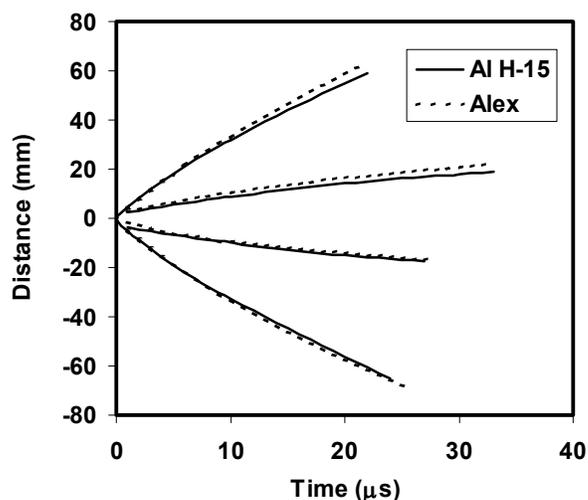


FIGURE 5. SHOCK AND EXPANSION HISTORIES FROM A 25.4 MM CYLINDER TEST

TABLE 5. SHOCK AND PARTICLE EXPANSION RADII AT 10 μ S

		Charge diameter (mm)	
		Mix	25.4
Shock radius	TNT/H-15	32.5 mm	37.2 mm
	TNT/Alex	32.6 mm	35.8 mm
Particle radius	TNT/H-15	9.3 mm	12.2 mm
	TNT/Alex	9.8 mm	13.4 mm

TABLE 6. RESULTS OF THE CRITICAL DIAMETER TESTS ON 160 MM LONG CYLINDERS.

Mix	Diameter of the Cylinder		
	20 mm	15 mm	10 mm
TNT/Al H-15 (80/20)	GO/GO	NO GO/NO GO	-
TNT/Al Alex (80/20)	GO/GO	GO/GO	GO/GO

d) Air-Blast Tests

Five types of explosives were tested: an inert PBX (PBXI-3 and PBXI-4, 20% Al), an energetic PBX (PBXE-1 and 2, 10% Al), a Tritonal-type explosive (TNT/Al 80/20), Comp. B with Al (10% Al) and ANFO/Al (10% Al). The complete results are presented elsewhere²⁹.

Figure 6 shows the results for plastic-bonded explosives. The PBXs with an inert binder are clearly under-performers for air-blast pressure, probably because of the inert materials content (16%) and because the Al is coated with polymer and does not react as efficiently. In addition, the curve for the mixture containing Alex is lower than the one with H-15. The energetic binder blends exhibit excellent performance, both with Alex and H-15. There is no noticeable difference in performance between the two Al types in energetic binder PBXs.

The melt-cast explosives demonstrated a lower performance with Alex (Figure 7). The TNT/Al spheres gave very low values of pressure and impulse (lower than CONWEP predictions for Tritonal). The spheres were probably too small (about 5 cm radius) to achieve an optimal performance. The Comp. B/Al charges produced pressures close to predicted (CONWEP) values. The performance of Alex in these charges was lower up to a distance of 2.5 meters, at which point both aluminum types gave the same pressure. In both cases, the impulse (not shown) was higher for Alex close to the charge. Lefrançois and Le Gallic¹⁶ have shown that Alex and 5 µm aluminum gave the same performance in air-blast tests of cylindrical charges.

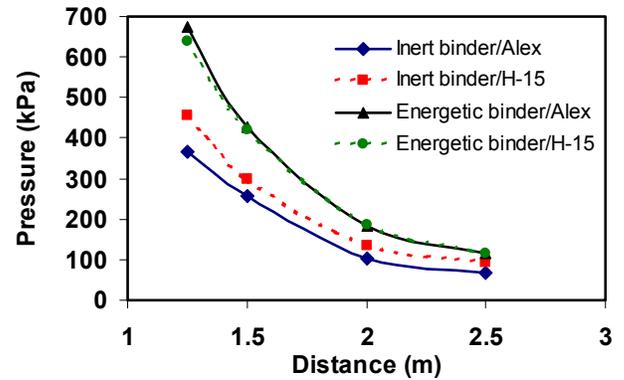


FIGURE 6. COMPARISON OF AIR BLAST PRESSURES FOR PBXS.

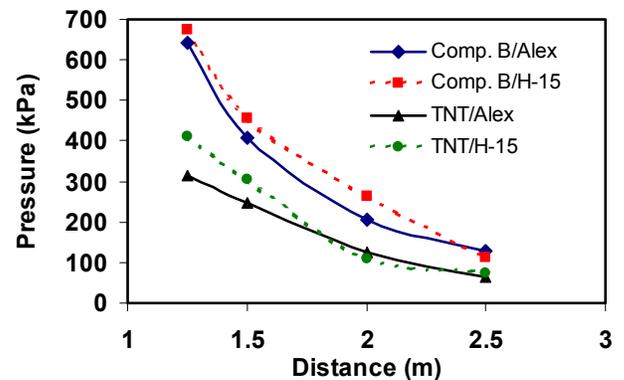


FIGURE 7. COMPARISON OF AIR BLAST PRESSURES FOR MELT-CAST EXPLOSIVES.

Both aluminum types in ANFO/Al mixtures produced the same performance in air-blast tests (Figure 8). The pressure values were high close and then much lower than for other explosives.

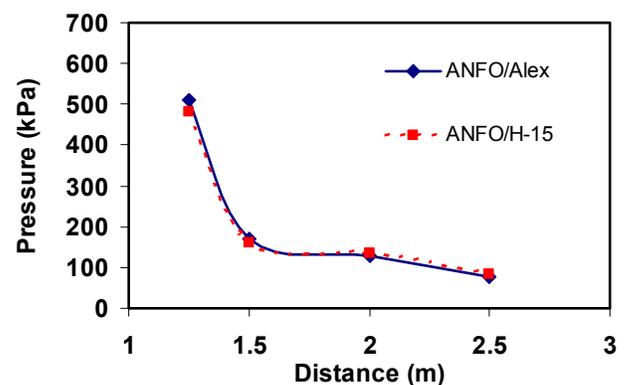


FIGURE 8. COMPARISON OF AIR BLAST PRESSURES FOR ANFO/AL EXPLOSIVES.

CONCLUSIONS

Nanometric aluminum did not increase the VoD of aluminised plastic-bonded explosives based on an inert binder. The performance (VoD) of PBXs based on an energetic binder was decreased when Alex replaced micrometric aluminum. In Composition B and ANFO, at 10% Al, Alex also reduced the VoD, but increased the heat of detonation. For Composition B blends, this may correlate with reported enhancements of the brisance effect by Alex. In TNT/Al mixes, Alex increases the VoD and the heat of detonation. The increase of VoD is more pronounced at small charge diameters, close to the critical diameter. No increase of pressure was found in aquarium tests. However, the expansion of the gases appears faster for Tritonal-type formulations containing nanometric aluminum. Alex was shown to decrease significantly the critical diameter of Tritonal-type mixes. There is no increase in air-blast performance by nanometric aluminum. In fact, for inert PBXs and melt-cast explosives, there seems to be a reduction of air-blast pressure.

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REFERENCES

1. Ivanov, G.V. and Tepper, F. "Activated Aluminum as a Stored Energy Source for Propellants," Fourth International Symposium on Special Topics in Chemical Propulsion, Challenges in Propellants and Combustion 100 Years after Nobel, Stockholm, Sweden, 27-28 May, 1996, pp. 636-644.
2. Mench, M.M., Kuo, K.K., Yeh, C.L. and Lu, Y.C. "Comparison of Thermal Behavior of Regular and Ultra-Fine Aluminum Powders (Alex) Made from Plasma Explosion Process," Comb. Sci. and Tech., Vol. 135, 1998, pp. 269-292.
3. Mench, M.M., Yeh, C.L., and Kuo, K.K. "Propellant Burning Rate Enhancement and Thermal Behavior of Ultra-Fine Aluminum Powders (Alex)," 29th International Annual Conference of ICT:

Energetic Materials, Production, Processing and Characterisation, Karlsruhe, Germany, 30 June – 3 July, 1998, pp. 30-1,15.

4. Cliff, M.D., de Yong, L., Edwards, D.P. and Watt, D.S., "Characterisation of Electroexploded Aluminium (Alex)", DSTO-TR-0818 (Limited Release), DSTO Aeronautical and Maritime Research Laboratory, Melbourne, Australia, 1999.

5. Jones, D.E.G., Brousseau, P., Fouchard, R.C., Turcotte, A.M. and Kwok, Q.S.M. "Thermal Characterization of Passivated Nanometer Size Aluminum Powders," Journal of Thermal Analysis and Calorimetry, Vol. 61, 2000, pp. 805-818.

6. Pranda, P., Prandova, K. and Hlavacek, V. "Particle Size and Reactivity of Aluminum Powders," Comb. Sci. and Tech. Vol. 156, 2000, pp. 81-96.

7. DeSena, J.T., and Kuo, K.K. "Evaluation of Stored Energy in Ultrafine Aluminum Powder Produced by Plasma Explosion," Journal of Propulsion and Power, Vol.15, No. 6, 1999, pp. 794-800.

8. Simonenko, V.N. and Zarko, V.E. "Comparative Studying the Combustion Behavior of Composite Propellants Containing Ultra Fine Aluminum," 30th International Conference of ICT, Energetic Materials: Modeling of Phenomena, Experimental Characterization, Environmental Engineering, Karlsruhe, Germany, 29 June – 2 July 1999, pp. 21-1,14.

9. Bashung, B., Grune, D., Licht, H.H. and M. Samirant "Combustion Phenomena of a Solid Propellant Based on Aluminum Powder," 5th International Symposium on Special Topics in Chemical Propulsion (5-ISICP), Stresa, Italy, 19-22 June, 2000.

10. Lessard, P., Beaupré, F. and Brousseau, P. "Burn Rate Studies of Composite Propellants Containing Ultra-Fine Metals," 32nd International Annual Conference of ICT, Karlsruhe, Germany, 3-6 July 2001, pp. 88-1,13.

11. Danen, W.C., Jorgensen, B.S., Busse, J.R., Ferris, M.J. and Smith, B.L. "Los Alamos Nanoenergetic Metastable Intermolecular Composite (Super Thermite) Program," 221st ACS National Meeting, San Diego, CA, 1-5 April 2001.

12. Reshetov, A.A., Shneider, V.B. and Yavorovsky, N.A. "Ultra Dispersed Aluminum's Influence on the Speed of Detonation of Hexagen," First All-Union Symposium on Macroscopic Kinetic and Chemical Gas-Dynamics, Vol. 1, Chernogolovka, Russia, October 1984.
13. Miller, P.J., Bedford, C.D. and Davis, J.J. "Effect of Metal Particle Size on the Detonation Properties of Various Metallized Explosives," Eleventh International Symposium on Detonation, ONR 33300-5, Snowmass, Colorado, 30 August – 4 Sept. 1998, pp. 214-220.
14. Tulis, A.J., Sumida, W.K., Dillon, J., Comeyne, W. and Heberlein, D.C. "Submicron Aluminum Particle Size Influence on Detonation of Dispersed Fuel-Oxidizer Powders," Arch. Comb., Vol 18, No 1-4, 1998, pp. 157-164.
15. Beaudin, G., Lefrançois, A., Bergues, D., Bigot, J. and Champion, Y. "Combustion of Nanophase Aluminum in the Detonation Products of Nitromethane," Eleventh International Symposium on Detonation, ONR 33300-5, Snowmass, Colorado, 30 August – 4 Sept. 1998, pp. 989-997
16. Lefrançois, A. and LeGallic, C. "Expertise of Nanometric Aluminum Powder on the Detonation Efficiency of Explosives," 32nd International Annual Conference of ICT, Karlsruhe, FRG, 3-6 July 2001, pp. 36-1,14.
17. Cliff, M.D., Dexter, R.M. and Watt, D.S. "The Effect of Electroexploded Aluminium (Alex) on Detonation Velocity and Pressure," DSTO-TR-0999 (Limited Release), DSTO Aeronautical and Maritime Research Laboratory, Melbourne, Australia, October 2000.
18. Brousseau, P. and Cliff, M.D. "The Effect of Ultrafine Aluminium Powder on the Detonation Properties of Various Explosives," 32nd International Annual Conference of ICT, Karlsruhe, Germany, 3-6 July 2001, pp. 37-1,14.
19. Katsabanis, P. "Development of a Detonation Calorimeter to Measure the Energy Output of High Explosives," Final report, Prepared for Defence Research Establishment Valcartier, April 1993.
20. Anderson, C.J. and Katsabanis, P. "*Evaluation of Heats of Detonation, Final Report*" from Mining Resource Engineering Limited, Kingston, Ontario, Prepared for Defence Research Establishment Valcartier, April 2000.
21. Anderson, C.J. and Katsabanis, P. "Heats of Detonation: Part II; Final Repor," from Mining Resource Engineering Limited, Kingston, Ontario, Prepared for Defence Research Establishment Valcartier, May 2001.
22. Berry, P., Cliff, M.D., Dexter, R.M., Mathys, G.I. and Watt, D.S. "Accelerated Ageing of Ultrafine Aluminium (Alex)," DSTO-TR-1244 (Limited Release), DSTO Aeronautical and Maritime Research Laboratory, Melbourne, Australia, November 2001.
23. Cooper, P.W. "Explosives Engineering", Wiley-VCH, New York 1996, p. 292.
24. Dorsett, H.E., Brousseau, P. and Cliff, M.D. "The Influence of Ultrafine Aluminum upon Explosives Detonation," 28th International Pyrotechnics Seminar, 4-9 November 2001, Adelaide, South Australia.
25. Suceska, M. "Test Methods for Explosives," Springer-Verlag, New York, 1995.
26. Anderson, C.J. and Katsabanis, P. "Aquarium Tests, Final Report," from Mining Resource Engineering Limited, Kingston, Ontario, Prepared for Defence Research Establishment Valcartier, May 2002.
27. McInstosh, G. "An Aquarium Test as an Explosive Performance Measure," DREV-TM-9426, Defence Research Establishment Valcartier, November 1994.
28. Hall, T.N. and Holden, J.R. "Navy Explosives Handbook," NSWC MP 88-116, Naval Surface Warfare Center, Dahlgren, Virginia, October 2000.
29. C.J. Anderson "Air-blast Measurements; Final Report", from Mining Resource Engineering Limited, Kingston, Ontario, Prepared for Defence Research Establishment Valcartier, January 2002.