Central European Journal of Energetic Materials
ISSN 1733-7178; e-ISSN 2353-1843

Cent. Eur. J. Energ. Mater., 2016, *13*(3), 557-566; DOI: 10.22211/cejem/65018

Experimental Studies on a High Energy Sheet Explosive Based on RDX and Bis(2,2-dinitropropyl) Formal/Acetal (BDNPF/A)

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Abstract: A plastic bonded explosive (PBX) in the form of a sheet explosive was formulated with 1,3,5-trinitro-1,3,5-triazinane (RDX) dispersed in a polymeric matrix of a thermoplastic linear polyurethane and a 50/50 wt.% eutectic mixture of energetic plasticizers, *viz.*, bis(2,2-dinitropropyl)formal (BDNPF) and bis(2,2-dinitropropyl)acetal (BDNPA) was used to increase the performance of the sheet explosive in terms of its velocity of detonation (VOD). The sheet explosives were prepared by a rolling process. Natural rubber (ISNR-5) based sheet explosive was taken as the standard composition. The study showed that the BDNPF/A based sheet explosive has a velocity of detonation of 7850 m/s, which is about 900 m/s higher than the standard composition. Thermal analysis of the sheet explosive formulations was performed using differential scanning calorimetry (DSC).

Keywords: sheet explosive, polyurethane, explosive reactive armour, BDNPF/A, RDX

1 Introduction

Conventional explosives based on 2,4,6-trinitrotoluene (TNT) have some major deficiencies, such as poor mechanical properties and rather high sensitivity towards external stimuli. Improvement in the sensitivity properties of these formulations can be achieved by the application of plastic binder systems.

A polymer bonded explosive (PBX) [1] is a composite material in which solid explosive materials like 1,3,5-trinitro-1,3,5-triazinane (RDX) / 1,3,5,7-tetranitro-1,3,5,7-tetrazocane (HMX) are uniformly dispersed in a polymeric matrix to provide flexibility as well as structural integrity/desired mechanical properties. PBXs in the form of flexible sheet explosives prepared by a calendering process can be formulated with both classes of polymers, *viz.*, polybutadienes and thermoplastic elastomers (TPEs). These flexible composite materials are known as sheet explosives [2-4]. A sheet explosive can be prepared by a rolling or extrusion process.

Nath *et al.* [2] and Mukundan *et al.* [3] have reported RDX as a major energetic ingredient in sheet explosive formulations with ethylene vinyl acetate (EVA) and Estane binder systems. These formulations were prepared by a rolling process. Pentaerythritol tetranitrate (PETN) based high energy sheet explosive formulations (DXD-19) with a thermoplastic elastomer (HyTemp-4454) and an energetic plasticizer bis(2,2-dinitropropyl)formal/acetal (BDNPF/A) has been reported by Park *et al.* [5]. This formulation was prepared by an extrusion process and the average value of the detonation velocity (VOD) was reported as 7200 m/s.

Sheet explosives are one of the most versatile explosive products, having dual use, *viz.,* military and civil. In addition to metal cutting, demolition and welding [6], sheet explosives are gaining tremendous importance as components of explosive reactive armour (ERA) [7-10]. ERA consisting of sandwiched sheet explosives offers effective protection to armoured vehicles, including tanks, against attack by projectiles and warheads based on the shaped charge concept.

Currently, natural rubber is used as a binder in sheet explosives. Generally, 7-15% rubber is used as the binder in sheet explosive compositions. However, rubber bonded sheet explosives have a limited shelf life due to the deterioration of rubber during storage, leading to loss of flexibility and structural integrity [11].

Joseph *et al.* [12] have reported hydroxyl terminated polybutadiene (HTPB) binder based sheet explosive compositions with an average VOD of 7200 m/s. A CL-20 based sheet explosive has also been reported with a VOD of 7680 m/s [13]. The major disadvantage of HTPB based sheet explosives is that the loading capacity of the energetic material in HTPB is only possible to a maximum of 85%.

A recent trend in the development of novel energetic formulations is to increase the performance of the explosive composition to its highest level without compromising the safety and the characteristic insensitivity properties. One of the approaches used by the energetic materials research community is to choose ingredients which are all energetic in nature to improve the energy of the system.

Due to the limitations of existing compositions, work on sheet explosives based on other synthetic polymers like polyurethane [14, 15] was initiated and the energy content was improved by incorporation of BDNPF/A as an energetic plasticizer [5]. Cellulose acetate butyrate was selected as a reinforcing agent for BDNPF/A to improve its mechanical properties.

In view of the above and in continuation of our work on sheet explosive formulations, we report here work on the development of sheet explosive formulations with suitable shock sensitivity and higher performance (VOD) which can defeat both types of threat, *i.e.* kinetic energy projectiles as well as chemical energy warheads. The sensitivity, performance and thermal analysis data obtained from BDNPF/A based sheet explosive formulation are compared with RDX/ISNR and RDX/PU based sheet explosive formulations.

2 Materials

1,3,5-Trinitro-1,3,5-triazinane (RDX) (particle size: 5-6 μm, density: 1816 kg/m^3) was used as the major energetic component and was obtained from the Ordnance Factory, Bhandara, India.

A linear thermoplastic polyurethane (PU) known commercially as Irostic P9820-19 ($\bar{M}_n$: 1.54×10^5, density: 1240 kg/m^3, glass transition temperature: −39.6 °C and softening point: 49.5 °C) was used as the binder and was procured from Huntsman Polyurethanes. The energetic plasticizers bis(2,2-dinitropropyl) formal (BDNPF) and bis(2,2-dinitropropyl)acetal (BDNPA) were used in a 50/50 wt.% eutectic mixture with 0.3% of 2-nitrodiphenylamine (2-NDPA) as stabilizer and referred to as BDNPF/A (density: 1390 kg/m^3 and melting point: −15 °C), were procured from commercial sources. Cellulose acetate butyrate (CAB-381-20) (specific gravity: 1.2 and $\bar{M}_n$: 70000) was used as a reinforcement agent and was procured from Eastman.

The natural rubber, known as ISNR-5, ($\bar{M}_n$: 8.2×10^5, density: 920 kg/m^3, glass transition temperature: −72 °C), was procured from a commercial source. 2-Butanone was used as the solvent for the preparation of a gel of polyurethane and CAB. Toluene was used as the solvent for the preparation of a gel of natural rubber.

3 Methods

3.1 Preparation of samples

The sheet explosive formulation was prepared by a solvent based method. The polyurethane (50 g) was dissolved in 2-butanone (425 mL) and allowed to form a gel. Simultaneously, cellulose acetate butyrate (CAB, 10 g) was dissolved in

2-butanone (425 mL) to form a gel. The polyurethane gel was transferred with BDNPF/A (40 g) to a steam jacketed sigma mixer and mixing was continued for 15-20 min. After this, RDX (900 g) was added to the binder mix in 2-3 portions and mixed for 2-3 h. Finally, the CAB gel was added and mixing was continued for 1 h.

In the case of the polyurethane-based sheet explosive formulation RDX (900 g) was mixed in the polyurethane gel (100 g). In the case of the standard composition, pieces of natural rubber (100 g) were dissolved in toluene (1200 mL) for gel preparation and RDX (900 g) was mixed into the gel.

During mixing, the maximum amount of solvent was evaporated by heating by circulating hot water through the jacket, leading to dough formation. Finally, a soft mass was obtained ready for rolling. The dough was rolled between two hot rollers into sheet form and cut into the desired dimensions.

3.2 Characterization methods

The theoretical maximum density (TMD) was calculated by using the formula:

$$\mathrm{TMD} = \Sigma \mathrm{W}_i/\Sigma(\mathrm{W}_i/\rho_i)$$

where: W_i is the weight percentage of component i, ρ_i is the density of component i. The experimental density of the sheet explosive was determined using Archimedes' principle. The sample (10×10 mm) was weighed both in air (W_1) and water (W_2) at 25 °C. The density (kg/m^3) was calculated as:

$$\mathrm{Density} = \mathrm{W}_1/(\mathrm{W}_1 - \mathrm{W}_2)$$

The mechanical properties of the sheets were determined using a Hounsfield Universal Testing Machine (capacity 25 kN) at a strain rate of 50 mm/min. The samples were prepared according to ASTM D638 type IV.

The sensitivity to impact stimuli of the sheet explosive formulations was determined by the fall hammer method (2 kg drop weight) as per the Bruceton staircase approach and the results are given in the terms of the statistically obtained 50% probability of explosion (h_{50}). A set of 25 experiments was conducted at height intervals of ±5 cm for each formulation. The figure of insensitiveness (FOI) was calculated as:

$$\mathrm{FOI} = (\text{median drop height of sample/median drop height of tetryl}) \times \text{FOI of tetryl}$$

The friction sensitivity was determined on a Julius Peters apparatus operating up to 360 N using standard methodology and subjecting samples until no explosion occurred in six consecutive tests [16, 17].

The shock sensitivity was measured by the aluminium block gap test by determining the minimum pressure of a shock wave that can initiate detonation of the sheet explosive sample (diameter 63 mm, thickness 5 mm). A cylindrical pressed RDX:Wax (95:5) donor charge of diameter 30 mm and height 100 mm, having a density of 1640 kg/m^3 and VOD of 8100 m/s, was used to generate the shock wave. The wave was allowed to pass through an aluminium block of diameter 63 mm of density 2700 kg/m^3, with the height being varied from 31 mm to 60 mm. The critical pressure (P) in kbar across the aluminium block by which the sheet explosive can be detonated with 50% probability was determined from the following relation [18]:

$$P = 172.3\ e^{-0.03205x}$$

where: P − critical pressure in kbar, x − thickness of the Al block in mm.

The velocity of detonation (VOD) was measured by the ionization probe technique. Pin type ionization probes (twisted enamelled copper wire) located at predetermined points were used at intervals of 30 mm as sensors for detecting the arrival time of the detonation wave. An oscilloscope (YOKOGAWA DL9140, 1 GHz) was used for data acquisition. Theoretical prediction of the VOD was carried out by using the Becker-Kistiakowsky-Wilson (BKW) code [19, 20]. The VOD trends for sheet explosive formulations were verified by theoretical calculations using the BKW code which is based on a FORTRAN executable code. The values of α, β, θ and κ were taken as 0.5, 0.16, 400 and 10.91, respectively, for the RDX data calculation to determine the theoretical VOD, where α, β, θ and κ are BKW equation constants. α is the repulsive potential term, β decides the slope of the density and VOD curve, θ prevents the pressure reaching infinity as the temperature decreases, and κ is determined by the co-volumes of the product components.

Thermal analysis was carried out using a differential scanning calorimeter (Perkin Elmer DSC-7) at a heating rate of 5 °C/min.

4 Results and Discussion

Different RDX-based sheet explosive formulations, namely RNR, RI and RIFA, respectively, were studied and are summarized in Table 1.

Table 1. Details of the RDX-based formulations

Sheet explosive formulation	Composition	Remarks
RNR	RDX/ISNR-5 (90/10)	Standard composition
RI	RDX/PU (90/10)	Reference composition
RIFA	RDX/PU/(BDNPF/A)/CAB (90/5/4/1)	Studied composition

The reference formulation (RI) gave a higher density than the standard formulation (RNR). The replacement of 4 parts of PU by the energetic plasticizer BDNPF/A and 1 part of PU by CAB led to an increase in the density of the formulation (RIFA). The experimental density was achieved at about 85-88% of the theoretical maximum density (TMD) of the sheet explosive formulations and is shown in Table 2.

The tensile strength (TS) of the RI formulation was found to be about 4 times higher than the standard formulation. The incorporation of BDNPF/A as partial replacement of polyurethane resulted in a decrease in the tensile strength, however, the flexibility was more than that of RI due to plasticization of the polyurethane by BDNPF/A.

Table 2. Mechanical properties of the sheet explosives

Formulation	Theoretical maximum density (TMD) [kg/m^3]	Density [kg/m^3]	TS [MPa]	Elongation [%]
RNR	1655	1430	0.6	80
RI	1735	1470	2.5	15
RIFA	1745	1540	0.5	44

The sensitivity characteristics of the RDX-based sheet explosive formulations are given in Table 3. In the impact sensitivity test, BDNPF/A incorporated formulations gave a higher h_{50} of 7.4 Nm compared to the standard formulation. However, the impact sensitivity of BDNPF/A based formulation was found to be almost similar to reference formulation. The friction sensitivity of BDNPF/A based formulation was found at 288 N, suggesting insensitivity to frictional stimuli. The shock sensitivity of formulation RIFA was found at 5.4 GPa, suggesting a more sensitive composition compared to the standard.

Replacement of 4% of the polyurethane by BDNPF/A led to remarkable increase in VOD of the formulation, by about 900 m/s, over the standard formulation shown in Table 3. This may be attributed to the higher density and incorporation of the energetic molecules (BDNPF/A), in place of polyurethane which is basically an inert material.

Table 3. Sensitivity and VOD characteristics of the formulations

Formulation	Sensitivity parameters				VOD	
	Impact		Friction insensitivity up to [N]	Shock [GPa]	Theoretical [m/s]	Experi-mental [m/s]
	h_{50} [N·m]	FOI*				
RNR	8.8	53	360	6.1	7235	6950
RI	7.6	48	360	5.6	7356	7200
RIFA	7.4	49	288	5.4	7700	7850

* FOI = Figure of Insensitiveness

A KE projectile, made from a metallic penetrator, to create a lower shock pressure on the target than a chemical energy projectile (explosive warhead), *i.e.* a more shock sensitive sheet explosive is required for initiation by a kinetic energy projectile. Thus, the BDNPF/A containing sheet explosives were found to be more sensitive in terms of impact as well as shock stimuli, and have a higher VOD compared to the standard formulation. Hence, this formulation can be used in explosive reactive armour to defeat KE projectiles as well as chemical energy projectiles. The formulation RIFA was evaluated in an ERA against a 125 mm shaped charge warhead, as well as a 125 mm fin stabilized armour piercing discarding sabot (FSAPDS) to achieve 70% and 30% reduction in penetration, respectively, which were higher than the standard formulation.

RIFA has longer shelf life than the standard formulation due to the synthetic polymer used as the binder instead of natural rubber. RIFA also had good flexibility and a higher VOD, suggesting that it can be used as a demolition device.

Thermal decomposition studies of pure RDX and the formulations RNR, RI and RIFA were carried out. A sample weight of about 1.4 mg was taken to study the thermal decomposition at a heating rate of 5 °C/min in the temperature range 50-350 °C as shown in Figure 1. The thermal analysis results demonstrated that RDX-based sheet explosive compositions decompose as a unified mix of RDX and polymer as a single exotherm, and were observed for all compositions by DSC. The endotherm (T_m) observed at 203-205 °C is due to melting of the RDX, and was followed by the decomposition exotherms (T_p) at 224-240 °C. The decomposition temperature for all formulations corresponded to that for RDX (233 °C) itself, suggesting that the explosive plays a pre-dominant role during the decomposition process. The onset temperature of the formulations was calculated from the exotherm and was observed at 214-218 °C. These results indicate the compatible nature of RDX with the binders and the thermal stability of the formulations.

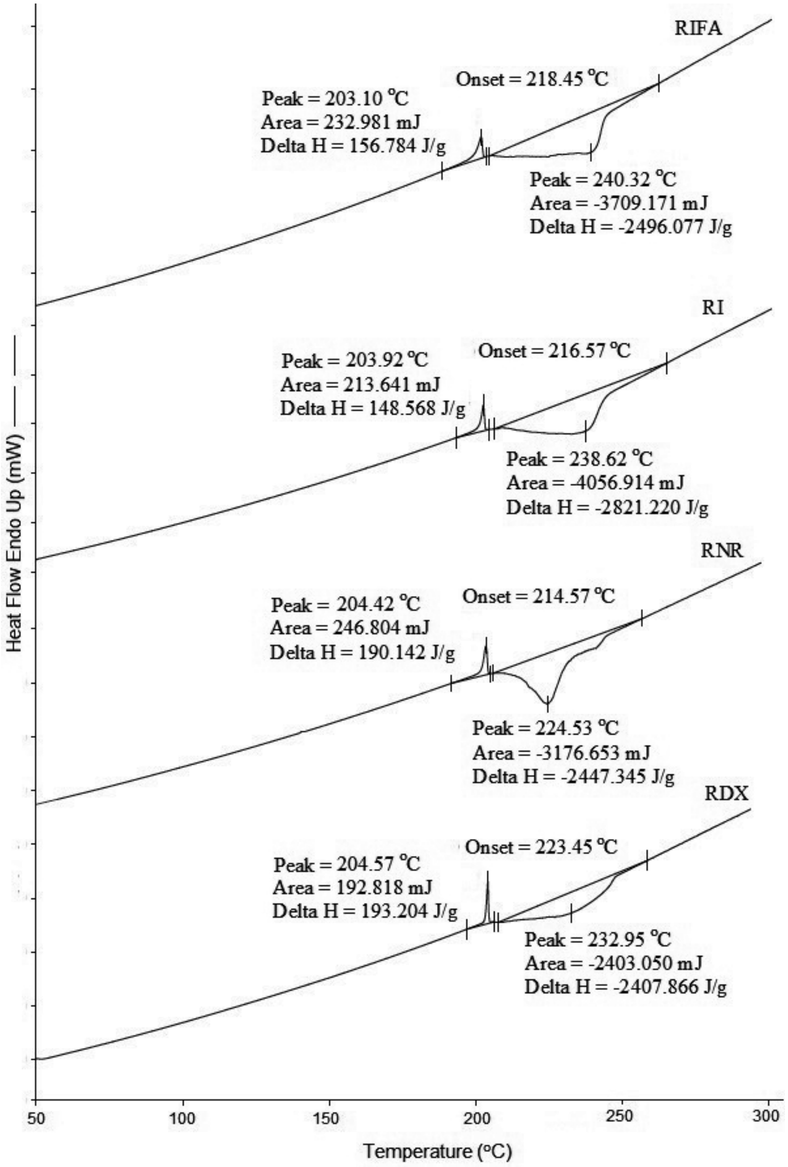

Figure 1. DSC curves for the decomposition studies of RDX, RNR, RI and RIFA formulations.

5 Conclusions

This research paper describes the preparation and characterization of an RDX and BDNPF/A based new high energy sheet explosive. The high performance sheet explosive developed in the present investigation may be used as a potential energetic component of an explosive reactive armour (ERA) system. The VOD of the formulation containing BDNPF/A as partial replacement of polyurethane was found to be superior to the ISNR-5 based standard formulation. The BDNPF/A containing sheet explosive was found to be more sensitive in terms of impact as well as shock stimuli compared to the standard RDX/ISNR-5 formulation. Hence, this formulation may be recommended for use in explosive reactive armour to defeat both types of threat, *i.e.* kinetic energy projectiles and chemical energy warheads. Thermal studies confirm the compatibility of the components of these formulations.

Acknowledgements
The authors are grateful to the Director, HEMRL, for his constant encouragement and for permission to publish this work.

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