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Exploring the Insensitive PBXs Allowing the Higher Performance of Inertial Confinement: European Defense Agency' Research and Technology Project "*RSEM-HPIC*"

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Abstract. Controlling the spatially localized kinetic instabilities in the Detonation Reaction Zone (DRZ) 3Dstructures provides a new way for designing the reduced sensitivity (RS) or insensitive (IS) PBX formulations allowing improving the performance of the explosively-driven inertial confinement (IC). The RS-PBXs having the homogeneous DRZ structure, are of considerable interest for application in precise ISmunitions, such as the or RS/IS-shaped charges and other RS/IS devices using the cumulation energy of convergent detonation, because they allow for minimization of the DRZ-induced local perturbation in the IC and further elimination of instabilities growth in the IC at its convergent motion. We present novel, physically justified concept for designing the high performance RS/IS-PBXs that implies in assembling the selected by size coarse RS-HE particles with the fine-grained RS/IS HE particles in binder, which formulation is pre-determined on the criterion of minimum kinetic disequilibrium in the DRZ between the coarse and fine crystalline fractions in binder. Paper summarizes experimental evidences provided argumentation of the criterion of *Minimum Kinetic non-Equilibrium in the DRZ Structure* as alternative to the principle of *Maximum Packing Density* of crystalline constituents conventionally applied for designing PBXs. Novel concept is currently under the extensive study by researchers of Coimbra University (PO), Fraunhofer ICT (DE), ISL (DE/FR) and MBDA ITALIA (IT), conducting in terms of the EDA Research Project "The Reduced Sensitivity Energetic Materials for the Higher Performance of the Inertial Confinement", RSEM-HPIC.

1. Introduction

The research consortium of University of Coimbra (PO, Leading Nation), Fraunhofer ICT (DE), MBDA ITALIA S.P.A (IT), and ISL - French-German Research Institute of Saint Louis endorse the European Defense Agency' Research and Technology Project entitled "The Reduced Sensitivity Energetic Materials for the Higher Performance of the Inertial Confinement", RSEM-HPIC [1,2].

The program addresses the development of new Insensitive Munitions in accordance with STANAG 4439 and AOP 39, with the particular emphasis on the shaped charges and other types of explosive devices applying the convergent detonations for driving Inertial Confinement (IC). The aim is to reduce the vulnerability, sensitivity to shock, and a probability of the accidental initiation, providing at the same time the higher performance of the explosively driven IC and, in case of shaped charges, the further effectiveness of the cumulative jets.

The specific goal is addressed to development of the Insensitive and Reduced Sensitivity PBX (IS-PBX, RS-PBX) formulations having highly homogeneous structure of the Detonation Reaction Zone (DRZ). Such formulations are enabling to provide the higher performance of the explosivelydriven metallic shells and cumulative jets by virtue of the minimized kinetic non-equilibrium in the DRZ between the coarse crystalline particles (RDX, HMX, RS RDX, RS HMX) and "dirty binder" (mixture of the fine and ultra-fine EM particles and micro and nano-size additives with the polymer binder) [5,7].

In this paper we shed a light on the novel criterion for designing the optimized IS/RS-PBX target formulations, with the emphasis on revealing the effect of kinetic localizations within DRZ structure on the dynamic performance of the PBX-driven copper-IC. The novel approach to attain a better performance of the explosively-driven metallic liners (and finally the higher effectiveness of cumulative jets), implies in equalizing between the detonation conversion kinetics of coarse crystalline fraction and "dirty binder".

2. Conceptual approach: Shaped-Charge Jet Performance vs. DRZ Quality

The RSEM-HPIC Consortium applies a novel concept for improving a detonation performance of the shaped IS/RS-PBX charges and further efficiency of the explosively-driven IC and cumulative jets. A concept implies in composing the RS-PBX formulations distinguished from the known prototypes by a highly equalized rates of detonation conversion between the coarse particles of the reduced sensitivity explosive material and a "dirty binder". Kinetic equilibrium between the detonation conversions of coarse RS-particles and "dirty binder" provides a dynamic and kinetic homogeneity of the DRZ structure and consequently, lesser deterioration of the IC caused by the DRZ' local perturbations [7].

Consequently, instead of the conventional "*Particles Maximum Packing*" criterion generally used at designing PBX formulations, a new "*Minimum Kinetic Non-Equilibrium*" criterion will be applied for elaboration of RS/IS-PBX compositions allowing a higher IC performance.

The relationship between the DRZ quality and a performance of the cumulative jet produced by a shaped-charge is as follows. In conventional PBXs, composed on the "*Particles Maximum Packing*" criterion, the detonation conversion kinetics of coarse HE particles and "dirty binder" are different in rate [3-7]. A difference between the kinetics of explosive components is significantly pronounced in case of RS-PBXs containing the coarse RS-RDX or RS-HMX particles [6]. Non-equilibrium between kinetics of detonation conversions results in *local perturbations (LP)* within the DRZ, such as *spatially localized reaction clusters* and *ejecta* [3-8]. The *characteristic size* of reaction clusters exceeds in minimum 6 times a mean size d_{50} of coarse explosive particles [5]. Within the DRZ, approximately 20% of detonation energy is localized in ejecta.

Local perturbations occurring in the DRZ produce an impact upon the IC that manifests itself in micro-perforation, swelling and over-heating of the boundary layer, and further origination and growth of wide spectrum *oscillating instabilities* [4-7]. The thickness of the IC-boundary layer, wherein *LPs* are dissipating to a heat, exceeds in minimum 6 times a size d_{50} of coarse HE particles [4, 7].

In real 3D-convergent motion of the IC, the dissipation of the *DRZ-induced LPs* is attended with the evolution of the *oscillating instability*. The *oscillating instability* is a main factor suppressing the explosively-driven IC focusing and cumulation [9].

Further impact upon the shaped-charge jet performance manifests itself in swelling, overheating and growth of local perturbations, and finally earlier jet fragmentation. The effect of the DRZ-local perturbations upon the jet fragmentation is revealed by the ISL researchers in experiments with the coarse-grained and fine-grained shaped charges [10].

The diagram presented in Figure 1 summarizes the relationship between Shaped-Charge Jet Performance vs. DRZ Quality.

Effect of kinetics non-equilibrium between the coarse HE particles and "dirty binder" on the reaction localizations, occurring in the DRZ structure, and the effect of the reaction localizationsand-ejecta upon the performance of copper confinement are described in [3-7].



Figure 1. The relationship between the Shaped-Charge Jet Performance and the DRZ homogeneity

3. DRZ Quality vs. Kinetic Equilibrium of PBX Components

Figure 2 illustrates the *effect of non-equilibrium between reactivity* of coarse-grained and finegrained HMX particles-in-binder upon the scale of perturbations occurring the DRZ as a result of kinetic localizations.

Local perturbations were spatially resolved in the DRZ-structures of two pores-less PBX materials, "HMX _{Class-3} 82/18 Epoxy" and "HMX _{Class-2} 82/18 GAP" (0.992TMD and 0.997TMD respectively), distinguished by particle sizes and binder (inert epoxy vs. reactive GAP). The HMX _{Class-3} particles had a density 1.894 g/cm³ and a mono-modal particles size distribution (PSD) with the mean size d ₅₀ =203.7 μ m. The HMX _{Class-2} particles had the bi-modal PSD at the mean particle size d ₅₀ = 16 46 μ m and a density 1917 g/cm³. Reactivity of the HMX _{Class-3} and HMX _{Class-2} particles was previously measured in the wedge tests of the HMX _{Class-3}/Water and HMX _{Class-2}/Water slurries, in which particles were subjected to 21.5 GPa shock. Higher reactivity of the HMX _{Class-2} in comparison with the HMX _{Class-3} particles is manifested by the 20%-faster time of shock to detonation transition (143 ns vs. 171 ns).



Figure 2. Discrimination between the scales of reaction localization spatially resolved in the DRZ structures of two PBX composites: 1^{st} with poorly equalized kinetics and 2^{nd} with the well equalized kinetics of the detonation conversion between the coarser particles and "dirty binder" (left and right fragments respectively). Application of the 96-channel Multi-Channel Optical Analyzer MCOA [3-8] provided the mesoscale probing of the DRZ through simultaneous measurements of the detonation speed D (including the local oscillations of the detonation front motion), and the time-resolved localizations in the stress field {P(t, X)} induced by the detonation in the standard optical monitor (Kapton stack monitor, KSM) and in the reaction radiance emitted from the DRZ surface.

Each 3D-plot represents a continuum of "*Pressure vs. time*" histories spatially resolved along the charge diameter with the 250 \pm 1 µm steps. The 3D-structures of the shock fields {*P* (*t*, *X*)} induced by the DRZ in the Kapton Stack optical Monitor (KSM) illustrate a strongly and slightly pronounced perturbations in the DRZs of the coarse-grained and fine-grained PBXs respectively.

Although the coarse-grained PBX "HMX _{Class-3} 82/18 Epoxy" has in $\approx 3\%$ higher detonation velocity than the VoD of the fine-grained PBX "HMX _{Class-2} 82/18 GAP" (8.30 mm/µs vs. 8.07 mm/µs), its DRZ contains strongly pronounced localizations, whereas the DRZ of the fine-grained composite bonded with the energetic binder GAP has much better equalized DRZ structure.

The ratio between the scales of local perturbations within the "kinetically worse-" and "kinetically better equalized" DRZ structures, allows predicting that, in the case of shaped charges,

the cumulative jet produced by the first PBX will be more perturbed and less effective than one produced by the second PBX.

Figure 3 illustrates the *effect of the kinetic non-equilibrium between the coarse HMX particles and "dirty binder"* upon the DRZ homogeneity in the examples of DRZ structures spatially resolved in the conventional PBX-1 and in the RS-PBX material PBX-2. The PBX-1 is composed with the conventional HMX coarse particles and mechanically comminuted fine HMX fraction: PBX-1 = HMX($d_{50}=106\mu$ m)/HMX($d_{50}=11.06\mu$ m)/HTPB, mixed with the mass ratio 60.8/15.2/24. The second explosive material, RS-PBX is formed by the RS-HMX coarse particles and the RS-HMX ultra-fine particles: PBX-2 (RS-PBX) = RS-HMX($d_{50}=104\mu$ m)/RS-HMX($d_{50}=1.64\mu$ m)/HTPB, mixed with the same mass ratio 60.8/15.2/24.



Figure 3. Long Charge Test instrumented with the Multi-Fiber Optical Probes (MFOP, [3-8]) for characterization of the DRZ quality and parameters of detonation performance. Both the detonation performance and the DRZ structure were characterized by way of simultaneous recording of the detonation front motion, the time-resolved DRZ-structure and the radiation field emitted from the DRZ surface.

The PBX-1 demonstrates a strongly non-equalized DRZ. The continuum of 1.5-2-mm-reaction localization spots is clearly resolved in its DRZ structure. Kinetic localizations are evidenced by

both the non-homogeneous reaction radiance field emitted from the DRZ surface and strongly perturbed shock field induced by the DRZ in optical monitor.

Although the RS-PBX material has in 1% lesser VoD than the conventional sensitivity material PBX-1 (8.20 mm/µs vs. 8.31 mm/µs), it demonstrates much better equalized DRZ structure. Comparison between the DRZ structures of PBX-1 and PBX-2 allows concluding that the RS-PBX material is preferable for application in the shaped charges.

Results presented in the Figure 3 support a general conclusion that incorporation of the novel *"kinetic equilibrium criterion"* is of considerable interest for designing the advanced RS-PBX materials, which are destined for the application in the IS/RS explosive devices containing the explosively-driven ICs. The reasonable kinetic equilibrium in the DRZ structure might be attained through variation of particles sizes of the coarse RS fraction and the mass-concentration of the RS "dirty binder" component.

4. The IC deterioration caused by the reaction localizations & ejecta in the DRZ surface

Deterioration of the PBX-driven IC is caused by reaction localizations and ejecta [4-6] occurring in the DRZ due to the non-equilibrium between kinetics of coarse HE particles vs. "dirty binder". The deterioration effect is considered below in the examples of two conventional PBX materials PBX-3 and PBX-4 and a copper IC.

The cast-cured PBX-3 formulation "HMX _{Class-3} ($d_{50} = 203.7 \ \mu\text{m}$) / HMX _{Class-2} ($d_{50} = 16.46 \ \mu\text{m}$) / energetic binder GAP was composed with the mass ratio of components 65.6/16.4/18 wt. % and with application of the "*Maximum Packing criteria*". The PBX-3 had a density $\rho_0 = 1.704 \ \text{g/cm}^3$ (0.974 TMD) and a VoD = 8.56 mm/µs.

The PBX-4 was a cast-cured material "HMX _{Class-2} 82/18 wt. % GAP" having the $\rho_0 = 1.759$ g/cm³ (0.998 TMD) and a VoD = 8.07 mm/µs.

Figure 4 illustrates experiments on spatially-resolved, real time measurements of the ejecta and reaction localization structures in the DRZ surface of PBX detonations. Streak camera records allow the fine resolution of the cellular structure in the DRZ surface and the size-quantification of multiple ejecta. Detonation cells represent the reaction localizations, triggered and driven by the dissipating ejecta. The detonation cells and ejecta are strongly pronounced in the PBX-3 detonation, proving that the DRZ of this explosive material is poorly equalized in kinetics. By rough estimations, approximately 20% of energy, released at detonation conversion of the PBX-3, is localized in the multiple ejecta.

The micro-photos of copper liners, recovered after the experiments with the PBX-3 and PBX-4, illustrate a significant difference between deteriorations caused in the IC by the *poorly equalized* and *better equalized* DRZ structures. In case of the PBX-3 detonation, the DRZ local perturbations produce the 0.8-1.2 mm-diameter craters in the IC surface. In case of the PBX-4 detonation, the DRZ-induced perturbations in copper IC are represented by 6-8 times lesser craters (0.1-0.2 mm-diameter). The micro-perforation is attended with the over-heating and swelling of the IC-boundary layer that is causing the compressibility losses at the mechanism of convergent IC motion.



PBX having the poorly equalized DRZ kinetics causes large, 0.8-1.2 mm-dia., craters in the IC surface.

The PBX with the well equalized DRZ kinetics causes in 6-8 times smaller craters in the IC surface (0.1-0.2 mm)

Figure 4. Time- and space-resolved measurements of the detonation front topography in the long charges of PBX-3 and PBX-4. The DRZ scanning tests were conducted on the PBX-3 and PBX-4 cylindrical charges having the 28-mm-diameter/20-mm-height and 5-mm-diameter/27.5-mm-height respectively. The PBX-3 and PBX-4 charges were incased in the 10-mm-steel and 20-mm-PVC confinement respectively. The PBX-3 self-sustained detonation was supported by the 100 mm-PE-4A booster of 25 mm-diameter. Streak records were conducted with application of the Electronic Streak Camera (ESC) Thomson TSN 506 N and the side-survey MFOP [7]. The left and right microphotos show different deterioration scales in the copper-liners recovered after experiments with the PBX-3 and PBX-4 charges of 80 mm-length and 5 mm x 10 mm cross-section (both incased in copper confinement.

The thickness of the IC-boundary layer, wherein the DRZ-induced local perturbations are dissipating to heat, exceeds minimum in 6 times the d_{50} -size of the coarse HMX fraction [4, 7].

Although the PBX-3 has the VoD in 6% higher than the VoD of PBX-4 (8.56 mm/ μ s vs. 8.065 mm/ μ s), the local perturbations generated in the copper-IC by the poorly-equalized DRZ of the PBX-3 are in 6-8 times grater in scale than in case of the PBX-4. Further, spatially-resolved measurements of shock field attenuation process in the copper-IC gave evidence that in case of PBX-3, local perturbations penetrate in the IC up to \approx 1.5 mm-thickness. In the case of the convergent motion, such perturbations lead to the origination and growth of the grater scale oscillating instability [9].

Experimental evidence presented above allows concluding that a performance of the shapedcharge jet might be enhanced through the improvement of the DRZ homogeneity. The PBX-4 explosive material will conduct a better cumulation and will produce more stable (less perturbed) cumulative jets than the PBX-3, because it has a better equalized DRZ.

5. Conclusive remarks

The summarized here experimental evidences point out that in the PBX materials composed on the classic criterion of maximum packing density of HE particles, the DRZ structures contain a wide spectrum of local perturbations caused by kinetic non-equilibrium between the coarse-grained fraction and "dirty binder". Local perturbations in the DRZ-structure manifest themselves by multiple ejecta of reaction products and the ejecta-driven detonation cells. Spatially localized perturbations of detonation flow are affecting the performance and compressibility of the PBXdriven inertial confinement, finally resulting in losses of cumulation quality, further instability generation, and earlier fragmentation of the cumulative jet.

When the RS/IS constituents are applied for PBX fabrication on the principle of maximum packing density, the resulted RS/IS PBX material demonstrates a higher non-equilibrium of the DRZ structure, when it compared with the conventional PBX. For achieving a higher IC performance and a greater cumulation order of the RS/IC shaped charges, the RS/IS PBX formulations must be optimized by equalizing the detonation kinetics of the RS-constituents: coarse fraction vs. "dirty binder". A novel approaches to improve the DRZ homogeneity in RS/IS PBXs (and consequently to enhance a dynamic performance of the IC) implies in assembling the selected RS/IS-HE particles coarse fraction with the "dirty binder", which formulation is pre-determined on the criterion of minimum kinetic disequilibrium in the detonation conversion zone.

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