Influence of Modified Energetic Materials on the Protective Effect of Reactive Armor

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Abstract. In order to improve the protective performance of reactive armor, the development course and present situation of reactive armor at home and abroad were described in detail, and the influencing factors of energetic materials on the protective performance of reactive armor were analyzed carefully. Finally, the protective performance of reactive armor of common type energy energetic and high energy energetic material was compared by numerical simulation and experimental verification. The results show that the protective ability of reactive armor can be improved by more than 10% compared with the common energetic materials reactive armor.

1. Introduction

In 1969, Professor Held in German proposed a reactive armor with a layer of explosive sandwiched between two plates, which is called “Sandwich” structure. This made a breakthrough in the research of reactive armor and obtained a patent. In 1982, in the war of invading Lebanon, Israel applied a kind of reactive armor called blazer to the main battle tank for the first time, which effectively reduced the threat of hollow charge warhead to armored vehicles[1]. Subsequently, reactive armor has been successfully used to deal with all kinds of anti tank armor penetrators with its concept of high ballistic efficiency, good security, light weight and small space occupation[2]. Since then, reactive armor has attracted wide attention all over the world. Britain and the former Soviet Union have applied reactive armor technology to tanks and armored vehicles one after another. Reactive armor has become an important part of modern armored vehicle protection system.

As the core energetic material of reactive armor, energetic materials have become the focus of attention all over the world. The special energetic materials for reactive armor have different characteristics from other insensitive explosives:

(1) Good ballistic performance. It can effectively defend large caliber armor piercing and penetrating projectiles;
(2) Reliable security performance. Anti explosion, shooting, dropping, gas cutting, fire, etc.

The performance of reactive armor energetic materials is the basis of reactive armor performance, and is the most critical core technology of reactive armor. The performance of energetic materials is determined by the formula performance and charging process. Therefore, the research on reactive armor energetic materials and charging process can effectively promote the development of reactive armor technology.

2. Development trend of energetic materials in reactive armor

2.1. Current situation and trend of reactive armor abroad

There are mainly two kinds of reactive armor in the United States, namely M19 reactive armor and M32 reactive armor. M19 reactive armor, Each square box is composed of four layer of explosive plates, the air barrier is between the plates. M32 reactive armor, with metal plates on both sides and energetic materials sandwiched in the middle. The energetic material used in M19 reactive armor and M32 reactive armor is PE explosive, which has the characteristics of low damage. In the Iraq war, when M19 reactive armor and M32 reactive armor are hit, the energetic material will explode, which will not damage the surrounding reactive armor components, and even the remaining energetic material plate in the components can still have a certain protective performance\(^\text{[6]}\).

Russian early kontakt-1 reactive armor used 4S20 explosive plate and PVV-5A explosive. PVV-5A explosive is a kind of semtin plastic explosive, the main component is RDX, accounting for about 90%. Other components are polyisobutene, which is heat sensitive explosive. KONTAKT-5 reactive armor used 4S22 explosive plate and PVV-12M plastic explosive, which is composed of 85% RDX and 15% inert desensitizer, with density of 1.5 g/cm\(^3\), detonation velocity of 7.76 km/s and TNT equivalent of 1.2 times. Relikt reactive armor uses 4S23 explosive plate, which is a kind of high energetic material and has higher explosive energy than PVV-12M plastic explosive.

At the present, Israel Raphael company is in the leading position in the research and development of reactive armor energetic materials in the world. The fourth generation of reactive armor developed by Israel Raphael company is called inert reactive armor. The reactive armor uses a new type of inert explosive with low burning rate, which combines the explosive layer with the emotional layer, and reasonably designs the sandwich structure to reduce the impact of explosion on vehicle and mounting bracket while reducing the penetration ability of metal jet. According to the latest report, Raphael has completed the development of the fifth generation reactive armor, which adopts the improved low burning rate explosive, which can effectively protect the explosive shaped warhead. From the development trend of reactive armor in various countries, it can be seen that on the premise of satisfying the protection capability, minimize aftereffect damage reactive armor has become to the mainstream.

2.2. Development Status and Trend of Domestic Reactive Armor

After 40 years of development, the domestic reactive armor technology has gone through five generations. It has developed from single reactive armor to the multi-purpose reactive armor of anti penetration, armor piercing and tandem warhead. Reactive armor energetic materials has also developed from the first generation of ordinary energetic materials to the second generation of ordinary energetic materials. With the emergence of new high-energy main explosives, a new
generation of high-energy energetic materials for reactive armor, energetic materials for special-shaped reactive armor, and new forms of explosives have been developed rapidly, and has greatly improved the anti-penetration ability of reactive armor.

3. Composition of energetic materials for reactive armor

3.1. Main explosive
The main explosive of the first generation energetic materials of the reaction armor at home and abroad is RDX, but the main explosive of the second generation energetic materials depends on the threat target. When large-scale tanks and armored vehicles are collided head-on, reactive armored vehicles are threatened by the large-caliber penetrating and armor-piercing warheads. The HMX explosives with higher energy is choose. In local urban street fighting or anti-terrorism operations, the armored vehicles are threatened by the medium and small-caliber individual armor-piercing bombs, so RDX explosive is sufficient to meet the protective performance as the main explosive, and the cost is lower.

With the maturity of active protection technology, the main target of reactive armor protection has changed from APHE(High Explosive Anti-Tank) to APFSDS, and the disadvantage of anti-APFSDS performance of reactive armor has been further amplified. Therefore, higher energetic materials should be selected for reactive armor in the future. In 1987, the HNIW (hexanitrohexaazaisowurtzitane) whose density was 8% higher than HMX, detonation velocity was 6% higher, detonation pressure was 8% higher, and energy density was 15% higher was synthesized by United States first[3]. The explosive formulation composed of HNIW and binder is expected to become the first choice for reactive armor in the future[8].

The friction sensitivity and impact sensitivity of HNIW are similar to those of HMX and RDX. The explosive temperature was lower than HMX, but higher than RDX and PETN. The electrostatic spark sensitivity is close to that of HMX and PETN. Foreign researchers have extensively studied the application of HNIW. French SNPE hope to improve its formulation performance by adopting different crystallization or grinding processes, and justing the quality parameters of HNIW, the GAP content of energetic binder. The United States, Japan, France, Switzerland and other countries are committed to the application of HINW in the formulation of rocket propellant and high-energy mixed explosive[4-6].

The physical parameter values and sensitivity of HNIW and HMX are shown in Table 1. The formulation performance of mixed explosive which based on HNIW and HMX are studied, and the results show that the former is improved by more than 12% than the latter; the penetration depth of the shaped charge of mixed explosives based on HNIW has increased significantly by 20%.

| Performance | HNIW ($\varepsilon$) | HMX ($\beta$) |
|-------------|----------------------|---------------|

Table 1. Comparison of partial performance between HNIW and HMX [6].
The insensitive agents commonly used to reduce the mechanical sensitivity of explosives include wax, high polymer and nitrocellulose compounds. Insensitive agents are generally non-explosive components, and the less the dosage is, the better, under the condition that the mechanical sensitivity of mixed explosives can meet the application requirements. For example: paraffin, according to the experimental test, when the proportion of 0.2%~1.0%, its impact sensitivity is not greater than 40%. However, when the proportion is 0.2%, the stability of impact sensitivity value is poor. Therefore, 0.5%~1.0% paraffin wax is generally used as insensitive agent.

Paraffin wax was generally used as the insensitive agent in the early reactive armor charge. With the casting explosive becoming the mainstream of military explosives, wax and high polymer are generally used as the insensitive agent in reactive armor charge at present, and even some energetic materials only use high polymer as the insensitive agent.

Binders directly affect the physical and explosive properties of explosives. Rubber, polyisobutene, resin and polytetrafluoroethylene were commonly used as binders, polystyrene-polyisobutene-polystyrene block copolymer, difluoramino substituted diethylene glycol, nitro polycarbamate, etc.

The choice of binder was determined by the state of energetic materials. For example, Russian reactive armor charge was Semetine plastic explosive or plastic explosive, so the binder generally chooses polyisobutylene, etc; American reactive armor charge is PBX explosive, so the binder is usually high polymer.  

Comprehensive analysis shows that the density, detonation velocity, and detonation pressure of the main explosive directly affect the functional force of the energetic material on the front and back plate, and then affect the interference ability of the front and back plate on the incoming ammunition; the insensitive agent is used to adjust the the sensitivity value of the energetic material, thereby ensuring the safety performance of the application in the reactive armor; the binders mainly affects the physical state of the energetic material, and is used to adjust the charge technology process ability of the energetic material. Therefore, the elementary explosive with high density, high detonation velocity and high detonation pressure is selected as the main explosive of the energetic material; on the premise of
meeting the requirements of sensitivity and charging process, the content of desensitizer and binder is minimized, then reducing its impact on the explosive properties of energy materials.

4. Influence of energetic materials on reactive armor

4.1. Simulation

The influence of energetic materials on reactive armor was studied by FEMAP software. The air medium is described by NULL model and Gruneisen state equation. Plastic_kinematic_material model and Gruneisen equation of state were used to describe the surface and back plane. Energetic materials are described by High_Exlosive_Burn model and JWL equation[7].

| Material No. | Density | Pressure Critical | Coefficient of viscosity | relative volume (tensile penetration) | relative volume (Compression penetration) | Young's Modulus | Poisson's ratio |
|--------------|---------|------------------|--------------------------|----------------------------------------|-------------------------------------------|-----------------|----------------|
| MID          | RO      | PC               | MU                       | TEROD                                  | CEROD                                    | YM              | PR             |
| 1            | 0.125E-02 | 0                | 0                        | 0                                      | 0                                         | 0               | 0              |

Table 3. Basic parameters of face and back plate materials.

| Material No. | Density | Young's Modulus (E) | Poisson's ratio (Pr) | Yield stress (Sigy) | hardening parameter (Beta) | failure index (FS) |
|--------------|---------|---------------------|----------------------|---------------------|-----------------------------|-------------------|
| Face and back plate | 7.85×10⁶ | 2.1×10⁹ | 0.25 | 250 | 1.0 | 0.05 |

Table 4. Basic parameters of energetic materials.

| Material No. | Density | Detonation | Chapman-Jouget Pressure | Chapman-Jouget Combustion Mark | Volume Modulus shear | Shear modulus | Yield stress |
|--------------|---------|------------|--------------------------|-------------------------------|----------------------|--------------|--------------|
| Mid          | Ro      | D          | PCJ                      | Beta                          | K                    | G            | Sigy         |
| General energetic Materials | 1.7 | 0.693 | 0.21 | 0 | 0 | 0 | 0 |
| High energy materials | 1.7 | 0.752 | 0.21 | 0 | 0 | 0 | 0 |

The simulation calculation model and calculation results of ordinary energetic materials and high-energy energetic materials are shown in Figure 1.

42μs high energy energetic material face and backboard transient.
42μs ordinary energetic material face and back board transient

Curve of velocity of the face and back board with high energy energetic material

Curve of velocity of the face and back board with common energy energetic material

**Figure 1.** Simulation results of ordinary energetic materials and high-energy energetic materials

According to the simulation results, the deformation of high energy energetic material surface and back plate is greater than that of ordinary energetic material surface and back plate, which is more conducive to jamming jet and armor-piercing projectile rod. The dispersion velocity of the high energy energetic material surface and the back plate can reach 1204.6 m/s, while that of the ordinary energetic material surface and the back plate is only 1078 m/s.

4.2. *Test Verification*

Based on "sandwich" structure reactive armor protection RPG-7 armour-breaking projectile, the comparison test of ordinary energetic material and high energy energetic material was carried out.
Ordinary energetic materials take RDX explosive as the main body, high-energy energetic materials take HMX charge as the main body, and the insensitive agent and binder are the same.

The test layout and test results are shown in Table 5 and Figures 2 and 3.

| Reactive Armor                                      | Protected Ammunition | Ammunition Power | Residual Penetration |
|-----------------------------------------------------|----------------------|------------------|----------------------|
| Common Energetic Material Generation                |                      |                  | 286 mmRHA            |
| "Sandwich" Reactive Armor                           |                      | RPG-7 HEAT       | 277 mmRHA            |
| High Energetic Material Generation                  |                      | 400 mmRHA        | 225 mmRHA            |
| "Sandwich" Reactive Armor                           |                      |                  | 232 mmRHA            |

**Figure 2.** Test of reactive armor with ordinary energetic material anti-RPG-7 HEAT.

**Figure 3.** Test of reactive armor with high energy energetic material anti-RPG-7 HEAT.

The experimental results show that the protective performance of reactive armor can be improved by about 11% with high energy materials. The experimental reactive armor structures were designed to the typical sandwich structure, and the main difference was that the energetic material is different. The face and back plate can be promptly drove by the energetic material which the main explosive is high-energy explosive, and the speed of the surface and back plate be increased more high, the action time that the reaction armor face and back plate interfere with the jet be extended more long. At last, the reducing penetration can be reached by reactive armor.

**5. Conclusion**
The following conclusions can be concluded by theoretical analysis, simulation calculation and experimental verification.

(1) The protective ability of reactive armor is improved significantly by adopting high-energy energetic materials under the same protective structure;

(2) The protective ability of reactive armor can reached a higher level, if the energetic material is changed to HNIW based explosives which energy is higher than HMX-based explosive.

(3) The charge technology of special-shaped reactive armor is different from the traditional sandwich structure, and its protection ability depends on the quality of the charge technology, therefore the charge technology of the special-shaped reactive armor with high-energy energetic materials is needed to further study.

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