STUDY ON THE LOW VULNERABILITY OF HMX-BASED EXPLOSIVES UNDER MECHANICAL STIMULATION

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In order to reduce the mechanical sensitivity of cyclotetramethylenetetranitramine (HMX) explosive and enhance its low vulnerability, HMX-based composite explosives were prepared by the water-suspension coating method based on orthogonal tests with HMX as the main explosive and epoxy resin as the binder. The properties of HMX-based composite explosives were tested by scanning electron microscopy (SEM) and X-ray diffraction (XRD). At the same time, the low vulnerability of HMX-based composite explosives under mechanical stimulation was calculated by the numerical simulation. The results show that the mechanical impact sensitivity of the prepared HMX-based composite explosive is better than that of single compound explosive HMX. The HMX-based composite explosive did not react more violently than the combustion under the mechanical stimulation source. The reaction degree of HMX-based composite explosive under mechanical stimulation meets the performance evaluation requirements of low vulnerability ammunition.

Key words: HMX; Orthogonal test; Performance test; Mechanical sensitivity; Low vulnerability

1. Introduction

The low vulnerability of ammunition is an insensitive property of the ammunition to external stimuli, that is, it exhibits good stability when subjected to an accident (friction or collision), a harsh environment (fire), or enemy attack (shock wave or high-speed fragments) [1, 2]. Low vulnerability ammunition can enhance the survivability of combatants and weapons, reduce the demand for storage, transportation and maintenance, and reduce the pressure of logistical support. Therefore, in order to adapt to the modern war environment and the demand of new weapons and ammunition, the researchers have carried out the vulnerability detection and evaluation and the development of low vulnerability ammunition through various ways[3-5].

In terms of vulnerability detection and evaluation, according to MIL-STD-2105D 'Hazard Assessment Tests for Non-Nuclear Munitions' and STANAG 4439 'Policy for Introduction and Assessment of Insensitive Munitions'[6, 7] , China has

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established test methods including fast cook-off test, slow cook-off test, bullet impact test, fragment impact test, sympathetic detonation test, jet impact test, and thermal fragment impact test, and has developed corresponding standards [8]. In the numerical simulation, the reaction degree of the ammunition is used to characterize whether the ammunition is ignited or exploded. When the reaction degree is 0, it indicates that the ammunition does not react. When the reaction degree is greater than 0.3, it indicates that the ammunition burns. When the reaction degree is greater than 0.5, it indicates that the ammunition is deflagration. When the reaction degree is 1, it indicates that the ammunition explodes[9, 10]. In addition, the different pressure and stress time history curves in the process of detonation, deflagration and combustion can more intuitively distinguish the reaction degree of ammunition[11]. Therefore, in the numerical calculation of the low vulnerability of the ammunition, the response level of the ammunition is determined by combining the reaction degree of the ammunition and the time history curves of pressure and stress.

Low vulnerability is the premise of large-scale production and application of weapons and ammunition. High-energy single compound explosive HMX is a hot spot of current research, but its wide application is limited due to its high mechanical sensitivity[12]. Therefore, it is an essential work to reduce the sensitivity of HMX and study its mechanical low vulnerability. At present, most studies mainly focus on the formulation, performance[13-16] and thermal safety[17, 18] of HMX-based explosives, and lack of low vulnerability research. Therefore, in this paper, a low vulnerability composite explosive was prepared based on single compound explosive HMX. The mechanical sensitivity of the composite explosive was tested and analyzed. The low vulnerability of HMX-based composite explosive under mechanical impact was studied by numerical simulation, in order to provide reference for the research of low vulnerability ammunition.

2. Preparation Test of Composite Explosive

2.1 Test Materials and Instruments

The materials used in the test are HMX、Ethyl acetate (99.5%) and Epoxy resin (E-44).

The main instruments used in the test include Electron analytical balance (FA1204B)、Precision electric stirrer (DJ)、Ultrasonic cleaning machine (KQ-50DA)、Vacuum drying oven (ZDF-6020)、Fourier transform infrared spectrometer ((PE)Spectrum Two) and Scanning electron microscope (COXEMEM-30Plus+).

2.2 The Orthogonal Optimization Test

In the process of preparing composite explosives, in addition to the performance of the main explosive and the binder itself, various factors involved in the preparation process will has a greater impact on the performance of the composite explosive, such as the amount of binder added and solubility, stirring speed and water bath temperature during the coating process. There are many factors to be considered in the water-suspension coating test. And the scale of the test is large. The orthogonal test can quickly determine the optimal parameter combination of the test. Therefore, the orthogonal test method is selected in this paper. According to the principle of 'neat' and 'uniform', some factors that have great influence on the preparation process of explosives are selected to carry out the test, so as to reduce the test cost and enhance the test efficiency[19-21].

Three levels were selected for each test factor in this paper. The test factor A is the ratio of explosive to water, which is 1: 6， 1: 8 and 1: 10, respectively. The test factor B is the binder content, which is 3 %, 5 % and 7 %, respectively. The test factor C is the stirring speed, which is 200 rpm， 400 rpm and 600 rpm, respectively. The test factor D is the water bath temperature, which is 30 ℃、40 ℃ and 50 ℃, respectively.

The factor-level table is shown in Table 1. On the basis of the orthogonal test, nine kinds of composite explosive samples with different preparation processes were obtained by water-suspension coating method. Table 2 is the preparation process table of epoxy resin coated single compound explosive HMX.

Table 1

Orthogonal test factors-level table

Level	Factor			
	A	B/%	C/rpm	D/°C
1	1： 6	3	200	30
2	1： 8	5	400	40
3	1： 10	7	600	50

Table 2

Preparation process table of epoxy resin coated HMX

Number	A	B	C	D
1	1	1	1	1
2	2	1	3	3
3	3	1	2	2
4	1	2	3	2
5	2	2	2	1
6	3	2	1	3
7	1	3	2	3
8	2	3	1	2
9	3	3	3	1

3. Performance Characterization of Composite Explosive

3.1 Mechanical Impact Sensitivity Analysis

The mechanical impact sensitivity of single compound explosive HMX and 9 groups of composite explosives prepared by the orthogonal test was tested. The test results were shown in Table 3.

Table 3

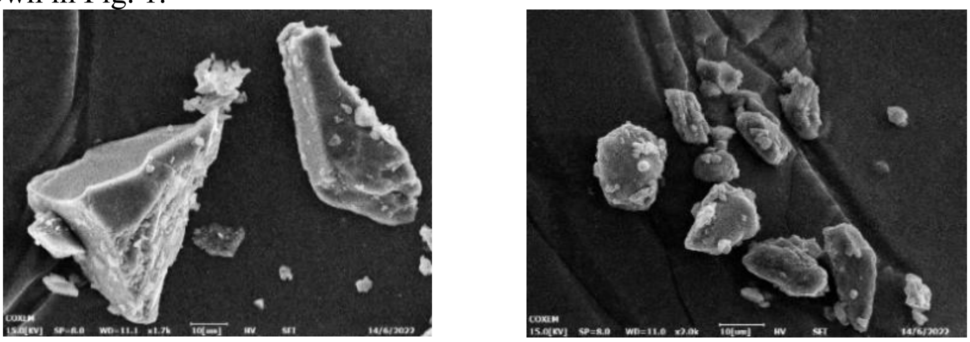
The Impact sensitivity table of single compound and composite explosive

Number	Explosive	Striking energy /J	The energy difference with the single compound explosive HMX /J
1	Single compound explosive HMX	2.00	——
2	Composite explosive 1#	6.00	4.00
3	Composite explosive 2#	2.00	0.00
4	Composite explosive 3#	4.00	2.00
5	Composite explosive 4#	2.50	0.50
6	Composite explosive 5#	3.00	1.00
7	Composite explosive 6#	4.00	2.00
8	Composite explosive 7#	3.00	1.00
9	Composite explosive 8#	3.50	1.50
10	Composite explosive 9#	2.00	0.00

From Table 3, it can be seen that compared with single compound explosive HMX, the impact energy of composite explosive 2# and 9# have no change, and the impact energy of 4# has little change, indicating that when the stirring speed is too high, the HMX particles in the composite explosive are exposed most. And the HMX particles are easy to produce friction between each other, forming stress concentration and high mechanical impact sensitivity. The impact sensitivity of the composite explosive 1# is significantly reduced, indicating that the surface coating of the composite explosive is more regular and complete under this preparation condition, which makes the HMX particles tend to be stable and reduces their sensitivity to external forces. Therefore, the mechanical impact sensitivity of composite explosive 1# is the lowest.

3.2 Morphology Analysis.

Scanning electron microscopy (SEM) was used to test the microstructure of single compound explosive HMX and composite explosive 1#. And the results were shown in Fig. 1.



a. Single compound explosive b. Composite explosive

Fig. 1. SEM images of single compound and composite explosive

Based on Fig. 1, the microscopic morphology analysis of the sample shows that the particles of single compound explosive HMX have obvious edges and corners. The particles of the composite explosive 1# have no obvious sharp edges and corners. And the edges and corners of particles are covered and smooth. The HMX particles are coated by the binder without leakage. And the coating layer is smooth and the coated particles are dense, which can effectively buffer the external impact and play an important role in reducing the sensitivity of single compound explosive HMX and improving mechanical vulnerability.

3.3 X-Ray Diffraction Analysis of Composite Explosives.

Fig. 2 is the XRD spectrum of single compound explosive HMX and composite explosive 1#. The composite explosive has the same diffraction peak position as the single compound explosive HMX, indicating that the crystal form of HMX in the composite explosive does not change during the preparation process, which is consistent with the performance before adding the binder. It is still a stable β -type. It shows that the coating process has high crystal control maturity.

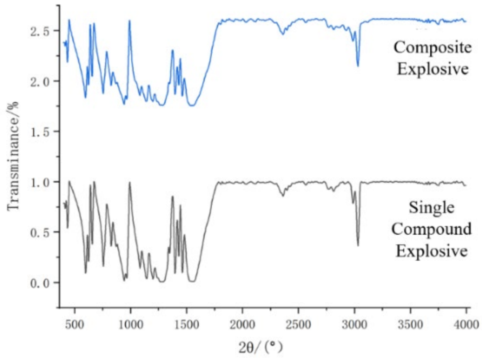


Fig. 2. X-ray diffraction patterns of single compound and composite explosive.

4. Numerical study on low vulnerability of explosives under mechanical stimulation

4.1 Numerical Calculation Model and Parameters

In this paper, the mechanical vulnerability of mixed explosive 1# is calculated by finite element analysis software LS-DYNA. The three-dimensional simulation models of bullets and fragments impacting explosives were established by Creo modeling software, as shown in Fig. 3 and 4. In the model, the explosive is installed in a cylindrical metal shell with a thickness of 1.5 mm, an inner diameter of 200 mm and a length of 403 mm. The bullet used the 12.7 mm bullet specified in the NATO standard vertebralization protocol STANAG 4241. The fragment adopts the 14.3 mm cone-head cylinder standard fragment specified in STANAG 4496. The three-dimensional solid unit is used to establish the simulation model, and the simulation model adopts the cm-g-us unit system. In order to better simulate the propagation process of shock wave in explosive when the explosive is impacted, the explosive and air are regarded as fluids and modeled by Euler grid. The Metal shell, bullet and fragment are regarded as solid and modeled by Lagrange grid. At the same time, the S-ALE algorithm is used, which can avoid the problems of large deformation and large distortion that may occur in the Lagrangian algorithm.

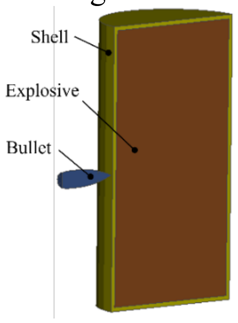


Fig. 3. Model diagram of bullet impact composite explosive.

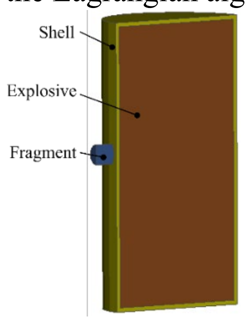


Fig. 4. Model diagram of fragment impact composite explosive.

In the numerical calculation model, the impact velocity of bullet is 825 m/s, and the impact velocity of fragment is 1880 m/s. The impact part is the central part in the axis direction of the cylindrical grain. The impact angle is perpendicular to the axis. The explosive shell, bullets and fragments are all metal. The Johnson-Cook model is used to describe the constitutive relationship of metals.

The Johnson-Cook model is suitable for the calculation of large strain and high strain rate. It can well describe the strain rate of metal materials. Its form is simple. It has been widely used in the calculation of impact explosion, penetration and other issues.

The relational expression of the Johnson-Cook model is as follows:

$$\sigma_{eq}=\left(A+B\varepsilon_{eq}{}^{n}\right)\left(1+C\ln\dot{\varepsilon}_{eq}{}^{*}\right)(1-(T^{*})^{m}) \quad (1)$$

where, σ_{eq} is the yield stress of the material. ε_{eq} is the equivalent plastic strain. $\dot{\varepsilon}_{eq}{}^{*}$ is dimensionless equivalent plastic strain rate. $T^{*} = (T-T_r)/(T_m-T_r)$ is the dimensionless temperature. T is the current temperature. T_r is the room temperature. T_m is the melting point temperature of the material. A, B, C, m and n are static yield stress, strain hardening modulus, strain rate correlation coefficient, strain hardening index and temperature correlation coefficient, respectively. The parameters of the constitutive model of metal materials are shown in Table 4[11, 22].

Table 4.

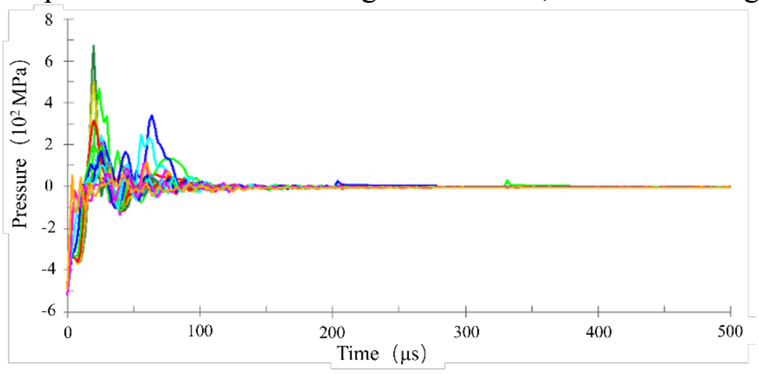
Parameters of Johnson-Cook constitutive model.

Name	ρ/(g·cm^{-3})	E/GPa	v	A/MPa	B/MPa	n	C	m
Shell	7.8	200	0.3	507	320	0.28	0.064	1.06
Bullet	7.85	210	0.33	1200	50000	1	0	1
Fragment	7.85	211	0.286	213	53	0.345	0.055	0.69

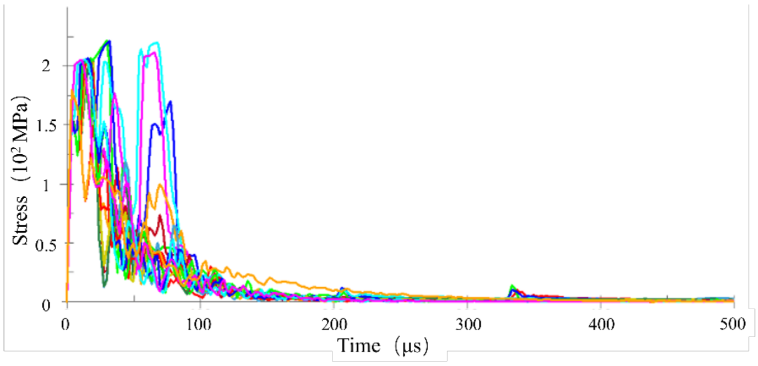
4.2 Numerical Results and Analysis

1) Analysis of Numerical Calculation Results of Bullet Impact.

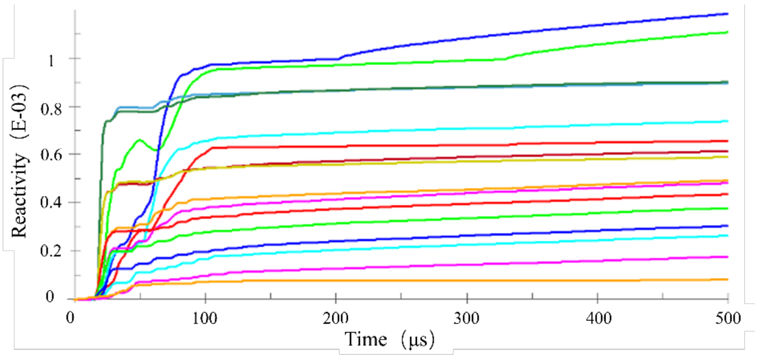
The time history curves of pressure, stress and reaction degree of explosives under bullet impact were obtained through calculation, as shown in Fig. 5.



(a) Pressure-time curves



(b) Stress-time curves



(c) Reaction degree-time curves

Fig. 5. The pressure, stress and reaction degree curves of explosive under bullet impact.

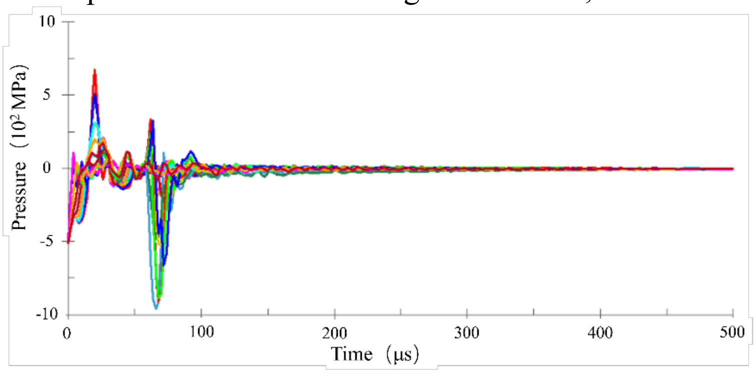
It can be seen from Fig. 5 (a) and (b) that the pressure and stress of the explosive increase in a short time under the impact of the bullet, and then decrease to 0. The pressure reaches the maximum value of 677 MPa at 20 μs. And the stress reaches the maximum value of 222 MPa at 30 μs. It can be seen from Fig. 5 (c) that the reaction degree of the explosive（see introduction） increases rapidly within 70 μs, indicating that the explosive reaction is the most intense during this time period. The reaction degree increases slowly after 70 μs. And the reaction degree reached the maximum value of 0.00119 when the reaction cut-off time was 500 μs.

Under the impact of bullet, the pressure and stress of the explosive suddenly rise and fall, and there is no stable value, that is, no stable detonation wave is formed. The maximum reactivity of the explosive is less than 0.3, so there is no combustion in the whole calculation process. However, combined with the change of the reaction time history curve, it can be judged that some of the explosives burn after being impacted by the bullet.

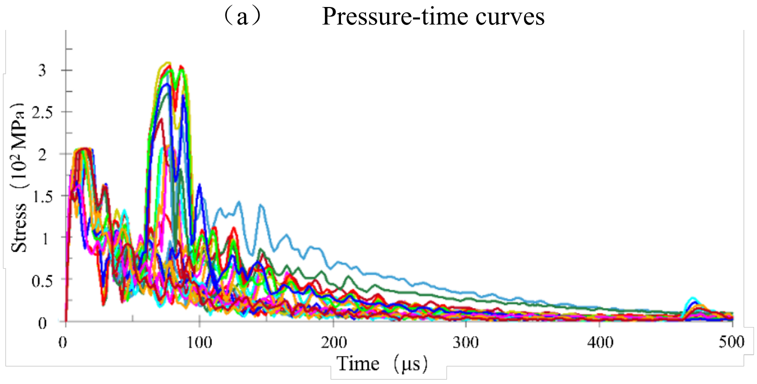
Therefore, combined with the changes of internal pressure, stress and reactivity of the explosive, it can be judged that the explosive does not react more violently than the combustion after being impacted by the bullet.

2) Analysis of Numerical Calculation Results of Fragment Impact.

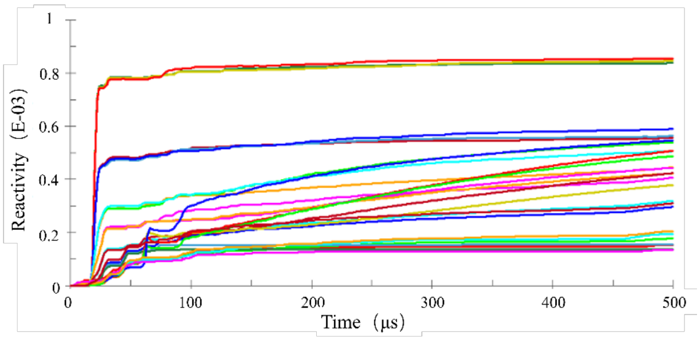
The time history curves of pressure, stress and reaction degree of explosives under fragment impact were obtained through calculation, as shown in Fig. 6.



（a） Pressure-time curves



（b） Stress-time curves



(c) Reaction degree-time curves

Fig. 6. The pressure, stress and reaction degree curves of explosive under fragment impact.

It can be seen from Fig. 6 (a) and (b) that the pressure and stress of the explosive increase in a short time under the impact of the fragment, and then decrease to 0. The pressure reaches the maximum value of 684 MPa at 20 μs. And the stress reaches the maximum value of 310 MPa at 78 μs. It can be seen from Fig. 6 (c) that the reaction degree of the explosive increases rapidly within 70 μs, indicating that the explosive reaction is the most intense during this time period. The reaction degree increases slowly after 40 μs. And the reaction degree reached the maximum value of 0.000858 when the reaction cut-off time was 500 μs.

Under the impact of fragment, the pressure and stress of the explosive suddenly rise and fall, and there is no stable value, that is, no stable detonation wave is formed. The maximum reactivity of the explosive is less than 0.3, so there is no combustion in the whole calculation process. However, combined with the change of the reaction time history curve, it can be judged that some of the explosives burn after being impacted by the fragment.

Therefore, combined with the changes of internal pressure, stress and reactivity of the explosive, it can be judged that the explosive does not react more violently than the combustion after being impacted by the fragment.

5. Conclusions

1. Compared with single compound explosive HMX, the coated composite explosive has good mechanical sensitivity after SEM, XRD and mechanical sensitivity test.

2. The preparation conditions of the composite explosive with the lowest mechanical sensitivity in the 9 groups of orthogonal experiments are as follows: the ratio of explosive to water is 1:6, the binder content is 3%, the stirring speed is 200 rpm, and the water bath temperature is 30 ℃.

3. In the numerical simulation, the composite explosive does not react more violently than combustion after being impacted by bullet and fragment, which meets the performance evaluation requirements of low vulnerability ammunition.

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