Research on the SDT technology based on a two-stage structure

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Abstract. The SDT (shock to detonation transition) technology based on a two-stage structure has been researched. The models of mass block’s velocity and shock-wave convergence produced from mass block impacting charge have been built, which reveal the mechanism of detonation caused by the impact. The influence characteristics of some parameters on the shock-wave convergence have been obtained. According to the analysis, the related parameters have been decided and the grop experiments were carried out. The result shows that the detonator employing the SDT structure, whose igniting time is less than 2ms, has good environmental adaptability. The technique of reliable and fast detonation of high explosive without using sensitive explosive has been realized.

1. Introduction

Currently most initiating explosive devices use traditional primary charges, such as LTNR and lead nitrate, which are quite sensitive and need quiet low energy to be initiated. However, there is great danger during the production, experiment, transportation, storage or usage of the devices which contain those charges. In order to reduce the risk of weapon system, there is a need in employing a new insensitive explosive train which contains no primary charges.

The technology of SDT based on a two-stage structure is introduced by H.Moulard and other researchers from French-German Research Institute of Saint-Louis and applied in the laser initiators. The first stage contains HMX mixed with 1% carbon black, which can be initiated by laser and produce high pressure to push a metal cylinder to go through a barrel. The second stage contains RDX, which is compacted by the cylinder and detonate. The structure is shown in figure 1.

![Figure 1. SDT laser detonator.](image)
The technology based on the two-stage structure was also applied in a safe and insensitive EED by Research Institute of Saint-Louis. This kind of EED, whose rated current is 5 A and the delay time is nearly 2 ms, is able to tolerate the experiments of 1A-1W-5min, 500 W AC/700 V pulse electric heating and temperature cycle of -84℃~+120℃. After the experiments mentioned above, the EED still has a good consistency of detonation.

This technology is also researched in Shaanxi Application Of Physical & Chemistry Institute. The first-stage charge are B/KNO₃ and HMX, and the second-stage charge is RDX. The initiators are shown in figure 2.

**Figure 2.** The initiators of Shaanxi Application Of Physical & Chemistry Institute.

In this paper, the SDT train based on a two-stage structure mainly includes ignition component, first-stage charge(insensitive pyrotechnic composition and high explosive), mass block, barrel and second-stage charge(high explosive), as shown in figure 3. Through the ignition component, the stimuli is given to the insensitive pyrotechnic composition, which then burns and initiate the high explosive in the first stage. The mass block is driven by the high-pressure gas generated from the high explosive and impact the high explosive in the second-stage charge, which detonates reliably through the convergence of shock wave.

**Figure 3.** The structure of SDT technology.

2. **Calculations of the mass block’s velocity**

2.1. *The block’s velocity model*

The velocity obtained from the deflagration of the primary charge is the initial velocity of the block, which is represented by $v_0$. Actually, there are many factors influencing $v_0$. To simplify the problem and push the contradiction forward, a few hypotheses are given as follows: 1) The deflagration of the primary charge is simultaneous. 2) The whole energy released from the charge transfers into the kinetic energy of the block, the kinetic energy of deflagration products and the internal energy of deflagration products. 3) Expanding velocities of deflagration products are linearly distributed.

According to the conservation of energy and the hypotheses mentioned above, the formulation determining the block’s velocity is
where \( m \) is the charge’s mass. \( E \) is the energy per unit mass of the charge. \( E_c \) is the block’s kinetic energy. \( E_g \) and \( E_e \) are the kinetic energy and the internal energy of the products from the primary charge separately.

The expression of the block’s kinetic energy is

\[
E_c = \frac{1}{2} M v_0^2.
\]

(2)

where \( M \) is the block’s mass.

The expression of the kinetic energy of the primary charge products is

\[
E_g = \frac{m}{6} v_0^2.
\]

(3)

The expression of the internal energy of the primary charge products is

\[
E_e = \frac{m g P}{\rho (\gamma - 1)}.
\]

(4)

where \( m, P \) and \( \rho \) represent the mass, the pressure and the density of the primary charge separately, and \( \gamma \) is the thermal insulation coefficient of the charge.

Substitute equation (2), equation (3) and equation (4) into equation (2) and we can obtain

\[
mE = \frac{1}{2} M v_0^2 + \frac{m}{6} v_0^2 + \frac{m g P}{\rho (\gamma - 1)}.
\]

(5)

From expression equation (5) we can obtain

\[
v_0 = [\frac{2mE - \frac{m g P}{\rho (\gamma - 1)}}{M + \frac{m}{3}}]^{1/2}.
\]

(6)

The structure of B/KNO₃+RDX was employed in the primary charge, in which the energy per unit mass of B/KNO₃ and RDX were \( E_1 \) and \( E_2 \) separately, and the charge’s mass are \( m_1 \) and \( m_2 \) separately. Then

\[
v_0 = [\frac{2(m_1 E_1 + m_2 E_2) - \frac{m g P}{\rho (\gamma - 1)}}{M + \frac{m_1 + m_2}{3}}]^{1/2}.
\]

(7)

The block comes into the accelerating barrel with the velocity of \( v_0 \), and its velocity becomes \( v_L \) at L point after accelerating in the barrel. To highlight the main contradictions and simplify the question, there are some assumptions as follows: 1) The inwall of the accelerating barrel is smooth (there is no friction between the block and the barrel). 2) The resistance loaded on the block’s right side is neglected. 3) The influence of the thermal diffusion on the mass velocity is ignored.

According to Newton’s second law and gas state equation. The block’s velocity \( v_L \) is

\[
v_L = [\frac{2 P_0 V_0}{M} \ln(\frac{V_0 + LS}{V_0}) + v_0^2]^{1/2}.
\]

(8)

where \( V_0 \) and \( P_0 \) are initial volume and initial pressure of the deflagration products separately.

2.2. Results and discussion

2.2.1. The relationship between the primary charge and initial velocity of the block According to the expression (9), the block’s velocity is mainly influenced by its mass \( M \), the mass of the primary charge
(m1 and m2) and etc. The initial velocities of the block corresponding to different primary charges were estimated with Matlab. The block’s mass was set to 100 mg and the estimated results are shown in figure 4.

![Figure 4](image-url)

**Figure 4.** The relationship between the mass of the primary charge and $v_0$.

As depicted in figure 4, the mass of the primary charge has a great influence on the initial velocity of the block; RDX makes more contributions to the initial velocity of the block than B/KNO3. Therefore, when the primary charge is being designed, its mass could be increased adequately to improve the initial velocity of the block; the mass ratio of RDX should be increased as possible on the premise of B/KNO3 being able to ignite RDX when determining the mass ratio of B/KNO3 and RDX.

2.2.2. The relationship between the block’s mass and the initial velocity The total mass of the primary charge is 79 mg, in which B/KNO3 is 12 mg and RDX is 67 mg. The initial velocities of the block corresponding to different masses were estimated, as shown in figure 5.

![Figure 5](image-url)

**Figure 5.** The relationship between the block’s mass and $v_0$.

It could be known from figure 5 that the block’s mass has a significant influence on the initial velocity, which could be improved from 2200 m/s to 3300 m/s theoretically as the mass changes from 150 mg to 50 mg. Therefore, in the case of satisfying other indexes, the mass should be reduced as possible and low density material should be employed.
2.2.3. The relationship between the length of accelerating barrel and the shock velocity The total mass of the primary charge is 79 mg, where B/KNO3 is 12 mg and RDX is 67 mg. The diameter of the barrel is 5 mm and the block’s mass is 100 mg. The velocities \( v_L \) of the block shocking the second-stage charge corresponding to different lengths of the barrel \( L \) have been estimated, as shown in figure 6.

![Figure 6. The relationship between the shock velocity and the barrel’s length.](image)

It could be seen from figure 6 that the length of the barrel has accelerating effect to some extent, while it is not as significant as the mass of the primary charge and the block’s mass; the block’s velocity just increases from 2270 m/s to about 2450 m/s (the variation less than 200 m/s), as the barrel’s length increases from 0 mm to 5 mm; the acceleration effect of the barrel reduces gradually with the barrel’s length increasing. Thus, the way of increasing the barrel’s length could not be used to lift the block’s velocity up greatly in the following design.

3. Simulations of the mass block shocking the second-stage charge

3.1. The block-shocking model

The interaction of mass block and the second-stage charge can be regarded as coaxial impact problem. Assumptions blow are made to simplify this problem: 1) The shock wave produced in the process is elastic. 2) The angle between the mass block’s velocity and the second-stage charge’s interface is 90°. 3) The initial stresses of the mass block and the second-stage charge are zero.

The process of the block shocking the second-stage charge was simulated by explicit dynamics software AUTODYN which is good at analyzing shock-wave transmission process. The structure was simplified rationally to make the question easy to analyze, as shown in figure 7. The block was a stainless steel cylinder of which diameter was 5 mm and thickness was 3 mm; the second-stage charge was RDX of which diameter was 3 mm and length was 8 mm; the constrained body was stainless steel of which diameter was 18 mm and length was 18 mm. When the mechanical behavior of the block shocking the second-stage charge was studied, RDX was regarded as an inert material, and only shock pressure distributions produced by impacts were analyzed. The materials involved were selected from AUTODYN-2D standard material library. Both the block and the constrained body were divided by Lagrangian mesh and coupled in the Euler field consisted of explosive and void material. Gauges were set along the axis of the second-stage charge and on the edge of the interface between the constrained body and the charge, as shown in figure 8.
3.2. Results and Analysis

3.2.1. Analysis of the impact process The velocity of the block was set to 600 m/s. There were some stress states at different time during the process of the block shocking the second-stage charge, as shown in figure 9. It can be seen that the pressure where the block contacted with the constrained body was much larger than that where the block contacted with the charge at the moment of the collision; as the time goes by, the higher pressure converged in the direction of the charge’s axis at a certain angle and reached the axis at 0.52 μs approximately, which made the pressure near the charge’s axis much higher than that where the block contacted with the charge. As shown in figure 10, there are pressure-time curves at different gauges. The peak pressure at gauge 6 where the block contacted with the constrained body was much higher than that at gauge 1 where the block contacted with the charge; the peak pressure at gauge 2 (the convergence point) was much higher than that at gauge 1. The phenomena mentioned above reveals the shock-wave effect in the two-stage SDT structure during the process of the block shocking the second-stage charge.

![Figure 7: Sketch of the model.](image1)

![Figure 8: Allocation of gauges.](image2)

Figure 9. Stress distributions at different time during the shocking process.
3.2.2. Effects of the material of the second-stage charge shell

The material of the second-stage charge shell was changed and the impact processes were simulated, in which the velocity of the mass block is 600 m/s. BRASS, COPPER, Al2024T351 and STEEL S-7 were chosen from the AutoDyn Material Library. Other setups stay the same. The stress distributions when the time is 0.53 ms with different materials are shown in figure 11.

![Figure 10](image1.png)

**Figure 10.** Pressure-time curves at different gauges.

![Figure 11](image2.png)

**Figure 11.** The stress distributions when the time is 0.53 ms with different materials.
The peak values of pressure at the gauge on the axis of charge with different shell materials are shown in figure 12. The material of the shell has a great influence on the shock-wave convergence. When the material is Al2024T351, the peak value is quite low, nearly 6.19 GPa; when the material is STEEL S-7, BRASS or COPPER, the peak values are 7.46 GPa, 7.59 Gpa and 7.80 GPa respectively.

3.2.3. Effects of the material’s hardness of the second-stage charge shell The material of the second-stage charge shell is STEEL S-7. The material’s hardness was changed and the impact processes were simulated, in which the velocity of the mass block is 600m/s. The hardness is changed by adjusting the material’s tensile strength. The range is HRC 20.0–HRC 50.0, while the tensile strength is between 740N/mm²~1725N/mm².

The peak values of pressure on the axis of charge with different hardness are shown in figure 13. The hardness has influence on the shock-wave convergence. As the hardness of the shell increases from HRC20.0 to HRC 50.0, the pressure produced in the shock-wave convergence decreased from 7.46 GPa to 7.10 GPa.
3.2.4. Effects of the diameter ratio between the second-stage charge and the mass block The material of the second-stage charge shell is STEEL S-7. The material’s hardness was changed and the impact processes were simulated, in which the velocity of the mass block is 600m/s. The hardness is changed by adjusting the material’s tensile strength. The range is HRC 20.0–HRC 50.0, while the tensile strength is between 740N/mm²~1725N/mm².

The diameter ratio between the second-stage charge and the mass block was changed and the impact processes were simulated, in which the velocity of the mass block is 600m/s. The diameter of the mass block stayed the same and the diameter of the second-stage charge changed. The ratio was set between 0.412–1.059. The peak values of pressure on the axis of charge with different ratios are shown in the figure 14. As the ratio increases, the peak value has a tendency of decrease. When the ratio increases from 0.412 to 0.529, the peak value changes unobviously, which drops from 8.74 GPa to 8.48 GPa. As the ratio continues to increase, the peak value falls apparently. After the ratio reaches the 0.765, the peak value keeps around 4.5GPa.

![Figure 14](image.png)

**Figure 14.** The peak values of pressure with different diameter ratio between the second-stage charge and the mass block.

The stress distributions of different diameter ratio between the charge and the mass block are shown in figure 15, which depicts that the effect of shock-wave convergence becomes weak gradually as the diameter ratio increases. When the ratio reaches 0.765, the pressure wave cannot converge in the axis of charge anymore.

![Stress Distributions](image.png)

(a) d/D=0.412  (b) d/D=0.529  (c) d/D=0.647
3.2.5. Effects of the mass block's velocity
The process of the mass block with different velocities, which ranged from 400 m/s to 800 m/s, impacting the second-stage charge was simulated. Initial peak values of pressure and those produced from shock-wave convergence during the process with different mass block’s velocities are shown in figure 16, which depicts that both values increase linearly along with the velocity.

The ratio of peak pressure and initial pressure mentioned above is defined as amplification factor. As is shown in figure 17, when the mass block’s velocity is between 400 m/s and 650 m/s, the effect of shock-wave convergence increases slowly along with the velocity; while the velocity becomes greater, the factor stays around 1.65.

4. Experiment

4.1. The experiment principle
The experiment principle is shown in figure 18. The power control unit(PCU) provides power to the diode laser and triggers the test system. Laser goes through an optical fiber and initiates the test specimen which then initiates the detonating fuse at the end. With the fuse functioning, the signal of the break of the ending target wire is sent to the test system. The test specimen is shown in figure 19.
The laser used in this test has a wavelength of 980 nm. The diameter of the optical fiber is 105 μm. The PCU is adjusted to make the output power of the fiber 2W.

4.2. Main parameters and performance test

Combined with the analysis above and experiment results from early work, the main parameters are decided. The first-stage charge is B/KNO₃(20 mg)+RDX (70 mg) and both densities are 1.5g/cm³. The mass block’s thickness is 1 mm, and the barrel’s length is 2 mm. Both diameters of the mass block and the barrel is 1.3 mm. The second-stage charge is RDX(30 mg) whose density is 1.5g/cm³. The diameter of the second-stage charge is 1.5g/cm³. There are ten specimens, and the results of igniting time T are shown in table 1.

| Sequence number | T [ms]   |
|-----------------|----------|
| 1               | 1.28ms   |
| 2               | 1.67ms   |
| 3               | 1.24ms   |
| 4               | 1.75ms   |
| 5               | 1.6ms    |
| 6               | 1.57ms   |
| 7               | 1.97ms   |
| 8               | 1.83ms   |
| 9               | 1.79ms   |
| 10              | 1.63ms   |

From the data above, all specimens can initiate detonating fuses reliably, which proves the feasibility of the SDT technology. The output performance is quite excellent for the igniting time is blow 2 ms.
4.3. Environmental test

The grope test for checking the specimens’ environmental performance has been completed. The test items and results are shown in table 2. The remains of specimens are shown in figure 20.

![Figure 20. The remains of specimens.](image)

| Group | Number | Test items | Result(igniting time)[ms]       |
|-------|--------|------------|---------------------------------|
| 1     | 3      | 2 m drop test | 1.78~3.24                       |
| 2     | 10     | Room temperature | 2.02~4.60                      |
| 3     | 10     | High temperature | 2.01~3.98                      |
| 4     | 10     | Low temperature | 1.74~3.88                      |

From the data above, all specimens can initiate detonating fuses after the environment test and igniting time is below 5 ms, which proves the design state of the specimen has a good environmental adaptability.

5. Conclusion

In this paper, the research focused on the SDT technology of two-stage structure was carried out. The related models have been built to reveal the mechanism of producing reliable detonation. Some parameters’ influences on the mass block’s velocity and characteristics of shock-wave convergence have been obtained, as given below:

1) The initial velocity of the block could be improved significantly by increasing the mass of the primary charge, to which RNX makes more contributions than B/KNO₃. Thus, the mass ratio of RDX should be increased as possible on the premise of B/KNO₃ being able to ignite RDX when determining the mass ratio of B/KNO₃ and RDX.

2) The block’s mass has a significant influence on the initial velocity, which could be improved from 2200 m/s to 3300 m/s theoretically as the mass changes from 150 mg to 50 mg.

3) The accelerating effect of the barrel’s length is not significant; the block’s velocity just increases from 2270 m/s to about 2450 m/s (the variation less than 200 m/s), as the barrel’s length increases from 0 mm to 5 mm; the acceleration effect of the barrel reduces gradually with the barrel’s length increasing.
4) When the BRASS, COPPER, Al2024T351 and STEEL S-7 is served as the shell’s material, the effect of shock-wave convergence can be produced from the process of the mass block impacting the second-stage charge. Among these materials, the effect produced in the shell of Al2024T351 is quite low, while the effect in the shell of STEEL S-7, BRASS and COPPER increases in turn. The effect decreases gradually as the hardness of the material increases.

5) When the diameter ratio between the second-stage charge and mass block is small, the effect of shock-wave convergence is significant. As the ratio increases, the effect becomes weak; while the ratio is over 0.765, the effect almost vanishes.

6) When the mass block impact the second-stage charge, the initial pressure and the peak pressure produced by shock-wave convergence increase linearly along with mass block’s velocity. When the velocity is between 400 m/s and 650 m/s, the effect of shock-wave convergence increases slowly; while the velocity is over 650 m/s, the amplification factor stays around 1.65.

Finally, an optimal design state was decided. The result of experiments shows that the state of specimens has good performance and robust environmental adaptability. The SDT technology has potential in engineering application.

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