Study on shock initiation of the charge covered by metal plate with penetrated notch

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Abstract. To analyze the coupling damage effect of high-speed fragments and near-field strong shock wave on the covered charge, a theoretical model of the shock initiation of the charge covered by metal plate with defects was established. The defect of the covered plate was simplified as an penetration notch, and the evolution characteristics of the shock wave in the notch were analyzed theoretically. The critical condition of the explosive detonation was determined by combining the explosive initiation criterion and the shock wave evolution characteristics. Take TNT covered by steel plate with a penetrated notch as an example, the nonlinear finite element program was used to simulate the shock initiation process of pressed charge, and the validity of the numerical simulation was verified by experimental results. The influence of the intensity of the shock wave, the thickness of the covered metal plate as well as the geometrical characteristics of the penetrated notch on the shock initiation of the pressed charge were analyzed by combining the theoretical model and numerical simulation results. The relationship of the notch size of the covered plate and the detonation distance was obtained by fitting, and the parameters n and K of the critical initiation criterion were obtained by least squares method. The theoretical calculation results and the numerical simulation results are agree with each other well and show that, the covered metal plate is beneficial for the protection of the charge. The existence of notch will weaken the protective performance of the covered plate, and the shape and size of the notch are also important factors that will affect the critical detonation distance of the charge. For the pressed TNT with and without 45# steel covered plate with the thickness 3 millimeters, the critical detonation distance of non-contact explosion was 13 millimeters and 81 millimeters, respectively. For the covered plate with a cylindrical notch, the critical detonation distance of the pressed TNT increases with increase of the diameter of the covered plate. For the covered plate has a frustum notch, the critical detonation distance of the pressed TNT decreases with increase of the slope in normal reflection.

1. Introduction

The study on the safety of the covered charge structure under strong external loading is of great significance to the development of weapons and ammunition. Shock waves and high-speed fragments are the two most common threats in battlefield environments. Therefore, the research on the shock initiation mechanism and damage effect of charging structure under the action of the above external energy will provide the basis for the safety design of charge ammunition [1, 2]. The structural characteristics of the covered plate are important factors that affect the detonation of the charge. At present, scholars have done some research on the shock initiation of fragments and fragment groups on
the covered charge structure [3-6] As for the study on the impact and detonation of explosives, F.E.Walker and R.J.Wasley [7] studied the impact and detonation characteristics of PBX-9404 and other explosives by experiments based on the theory of thermal detonation, deduced \( p^t = C \) as the initiation criterion of the famous heterogeneous explosives, which provided a theoretical basis for the impact and detonation study of insensitive ammunition. J. P. Lu et al. [8] numerically simulated the sympathetic detonation experiments of the bare-boned PBXN-109 explosive. The impact of explosive shock waves on bare explosives was studied. P. W. Howe et al. [9] carried out the Euler program to perform the sympathetic detonation experiments of the covered charge by a two-dimensional numerical simulation. The effect of the explosion shock wave on the acceptor charge at a small sympathetic detonation distance was analyzed and calculated. The influence of the thickness of the shell, the sympathetic detonation distance, the donor explosive and the covered plate on the sympathetic detonation are obtained. Wang Chen et al. [10] carried out a numerical simulation on the sympathetic detonation experiments of the GHL explosives in steel shell, and analyzed the influence of the thickness of the donor charge shell on the sympathetic distance. At present, as an important aspect of ammunition security research, the response of charge covered by metal plate with defect under the action of super close field intensity shock wave is rarely reported. Therefore, it is necessary to carry out the research on the shock initiation of the explosive shock wave to the charge covered by metal plate with defects, so as to provide guidance for the safety design of ammunition.

In this paper, taking the pressed TNT as an example, and the covered plate is 45 × steel. The shock initiation model of the charge covered by steel plate with defects under the near-field strong shock wave is established theoretically. The numerical simulation method is used to study the shock initiation effect of the charge covered by steel plate with defects under the near-field strong shock wave. The effectiveness of the numerical simulation is verified by the test, and the influence of different notch sizes and initiation of the covered plate are analyzed by theoretical calculations and numerical simulations. The critical initiation conditions are determined by the distance effect on the shock initiation.

2. Theoretical analysis of the near-field explosion shock wave on shock initiation of the charge covered by metal plate with defects

The shock initiation model of the charge covered by metal plate with defects studied in this paper is shown in figure 1. This charge covered by steel plate with defects includes donor charge, covered plate with penetrating notch and acceptor charge, the donor charge radius is \( r \), the covered plate is in close contact with the acceptor charge, the thickness of the covered plate is \( H \) and the gradient is \( \alpha \). In this paper, the cylindrical charge is equivalent to the spherical charge structure of equal mass. Based on the two-dimensional assumption of shock wave plane and neglecting the influence of sparse wave, we analyze the evolution process of shock wave by using the reflection and superposition principle of shock wave, which includes the propagation of shock wave in the air and the reflection and superposition of shock wave at the through notch of covered plate.

![Figure 1](image.png)

**Figure 1.** Schematic of shock initiation of the charge covered by metal plate with penetrated notch.
2.1. The propagation of shock waves in the air
The so-called infinite air means that the explosion source is high enough from the ground. At this time, the ratio height must meet: \( \frac{h}{W} \geq 0.35m \cdot kg^{-1/3} \), where \( h \) is the explosion height, that is, the distance from the ground. Explosive explosion in uniform atmosphere [11]:

\[
\Delta P = \frac{0.084}{R} + \frac{0.27}{R^2} + \frac{0.7}{R^4} (1 \leq R \leq 10 \sim 15) \tag{1}
\]

\( \Delta P \) is the peak overpressure of shock wave when explosive explodes in the uniform infinite air, \( R = \frac{h}{W} \) is defined as scale distance, where \( h \) is the distance from the explosion center. \( W \) is the TNT equivalent weight of explosive; \( W = W_0 \frac{Q_{ei}}{Q_{oTNT}} \), \( W_0 \) is the mass of this explosive; \( Q_{ei} \) is the explosive heat; \( Q_{oTNT} \) is the explosive heat of TNT, \( Q_{oTNT} = 4187J/kg \).

Baker formula can be used to calculate the peak overpressure of air shock wave for infinite air explosion in a larger or smaller range [11].

When \( 0.05 \leq R \leq 0.5 \),

\[
\Delta P = \frac{2.036}{R} + \frac{0.194}{R^2} + \frac{0.094}{R^3} \tag{2}
\]

When \( 0.5 \leq R \leq 70.9 \),

\[
\Delta P = \frac{0.067}{R} + \frac{0.301}{R^2} + \frac{0.431}{R^3} \tag{3}
\]

\( \Delta P \) is calculated from above, and according to the derivation calculation formula of shock wave:

\[
P_1 - P_0 = \frac{2}{\gamma + 1} \rho_0 D^2 (1 - \frac{c_0^2}{D^2}) \tag{4}
\]

\[
u_1 - \nu_0 = \frac{2}{\gamma + 1} (1 - \frac{c_0^2}{D^2}) \tag{5}
\]

\[
\frac{\nu_1}{\nu_0} = \frac{2}{\gamma + 1} (1 - \frac{c_0^2}{D^2}) \tag{6}
\]

It can be obtained that:

\[
D = 340 \sqrt{1 + 0.85 \times 10^{-5} \Delta P}, \quad u_1 = \frac{2.4 \times 10^{-5} \Delta P}{\sqrt{1 + 0.85 \times 10^{-5} \Delta P}}, \quad \rho_1 = 1.225 \frac{7.08 \times 10^5 + 6 \Delta P}{7.08 \times 10^5 + \Delta P}, \quad T_1 = 288 \frac{(1 + 10^{-6} \Delta P)(7.08 \times 10^5 + \Delta P)}{7.08 \times 10^5 + 6 \Delta P}.
\]

Where \( P_0, \rho_0, \ c_0, \ \nu_0, \ u_0 \) are the pressure, density, sound velocity, volume and particle velocity of undisturbed medium parameters in the air respectively, and \( \rho_0 = 1.293kg/m^3, \ c_0 = 340m/s \), \( u_0 = 0, \ \gamma = 1.4, \ P_1, \ \rho_1, \ T_1, \ u_1 \) are the pressure, density, temperature, particle velocity of the air at the shock wave front and D is shock wave velocity, respectively.

2.2. Reflection of shock wave
The reflection of shock wave on the wall can be divided into three types: positive reflection, regular oblique reflection and Mach reflection. The normal reflection of shock wave and detonation wave on solid wall, the reflection of air shock waves generated by point explosion on the ground surface or the collision of two waves of equal intensity in the condensed medium will show the normal reflection phenomenon, for the normal reflection of shock wave in ideal gas, the analytical solution can also be obtained. As shown in figure 2, we suppose that there is a plane shock I, which projects obliquely on the solid wall S, the angle between the wave front and the solid wall is \( \alpha_0 \). From figure 2 we can know that \( \alpha_0 = \alpha \). When the incident angle \( \alpha_0 \) is small, the normal reflection occurs. The intersection point of the reflected wave front R and the incident wave front I is located on the solid wall at O, which also propagates forward with the incident wave, and the intersection point O moves forward along the solid wall. Assuming that the velocity of incident wave in the laboratory coordinate system is D, the fluid velocity, pressure, density and sound velocity after the wave are \( \nu_1, \ P_1, \ \rho_1, \ c_1 \), respectively, and that the wave front is assumed to be stationary in this coordinate system.

It can be seen from the geometric relationship in figure 2 that the velocity of point O along the solid wall is:
\[ q_0 = \frac{D}{\sin \alpha_0} \]  \hspace{1cm} (7)

In this paper, the flow velocity in the laboratory coordinate system is specified as \( u \), the flow velocity in the moving coordinate system is specified as \( q \), and the direction of the vector \( q_0 \) is selected to be opposite to that of the point \( O \) in the laboratory coordinate system, then:

\[ q_t = u_t + q_0 \]  \hspace{1cm} (8)

From the vector diagram of figure 2, we can obtain:

\[ q_1^2 = (q_0 - u_1 \sin \alpha_0)^2 + u_1^2 \cos^2 \alpha_0 \]  \hspace{1cm} (9)

\[ \tan \theta_1 = \frac{u_1 \cos \alpha_0}{q_0 - u_1 \sin \alpha_0} \]  \hspace{1cm} (10)

Where in \( \theta_1 \) is the angle between \( q_0 \) and \( q_1 \). When rotating counterclockwise from \( q_0 \) to \( q_1 \), the angle is positive. As can be seen from figure 2 that if \( q_1 \) flows obliquely to the solid wall and the shock wave is supersonic, which means \( q_1 > c_1 \), then the reflected wave will also generate shock wave. Therefore, according to the Hugoniot relationship and the shock pole curve relationship of shock wave, we can get:

\[ \tan \theta_2 = \pm \sqrt{\frac{(\rho_2 - \rho_1)(\frac{1}{\rho_1} - \frac{1}{\rho_2})}{q_1 - \frac{p_2}{\rho_1} - \frac{p_1}{\rho_1}}} \]  \hspace{1cm} (11)

\[ \varepsilon (p_2, \rho_2) - \varepsilon (p_1, \rho_1) = \frac{1}{2} (p_2 + p_1) \left( \frac{1}{\rho_1} - \frac{1}{\rho_2} \right) \]  \hspace{1cm} (12)

The relationship between \( (p_2, \theta_2) \) on the reflected shock wave can be obtained by combining formulas (11) and (12), where \( p_2 \) is the pressure after the reflected wave, \( \theta_2 \) is the angle between \( q_1 \) and \( q_2 \). Since the incident and reflection of shock wave are connected with the solid wall, the corresponding solid wall conditions must be meet: \( q_2 \parallel q_0 \), that is, the velocity of the fluid is rotated by \( \theta \) through the incident wave, and then it also need to turn back to the original \( q_0 \) direction through the reflected wave. Therefore, the above conditions can be written as: \( \theta_1 + \theta_2 = 0 \), which is the definite condition for a normal reflection. If air is assumed to be an ideal gas, the necessary conditions for the existence of normal reflection can be obtained according to equations (9) and (10), as shown in equation (13), it can be seen from the following formula that the normal reflection may not exist before \( \alpha_0^* \) is reached. According to the formula in Section 1.1 of this paper, \( \alpha_0 < 70^\circ \) is obtained, which all meet the conditions of normal reflection.

\[ (\cot \alpha_0)^2 \geq \frac{c_1^2 - (u_1 - u_0)^2}{u_1^2} = (\cot \alpha_0^*)^2 \]  \hspace{1cm} (13)

Normal reflection can be solved by iterative method. In the case of a given incident wave state \( p_1, \theta_1 \) and \( q_1 \) can be calculated by formulas (9) and (10), \( \rho_2 \) is given by experimental method, substitute in formula (11) and (12) to get \( \theta_2 \) until the error range given by the solid wall condition is satisfied.

![Figure 2. Reflection diagram of shock wave on solid wall.](image-url)
2.3. Superposition of shock waves
The interaction of two collision shock waves with the same strength is equivalent to the reflection process of shock wave on the rigid wall. The calculation formula of reflection overpressure of shock wave on the rigid wall is as follows:

$$
\Delta P_d = \Delta P \left[ 2 + \frac{\cos \theta}{B} + \frac{(\gamma+1) \Delta P}{(\gamma-1)\rho_0 + 2\rho_0 \cos^2 \theta} \right]
$$

(14)

Where $\theta$ is the angle between two shock wave fronts, and $B$ is determined by the continuous condition of reflection parameter when $\theta = \theta_{cr}$.

$$
B = \begin{cases} 
\cos \theta & \theta \leq \theta_{cr} \\
\cos \theta_{cr} & \theta \geq \theta_{cr}
\end{cases}
$$

(15)

Where $\theta_{cr}$ is the critical incident angle.

Considering the characteristics of $\theta_{cr}$ varying with the shock wave intensity, the approximate calculation formula of $\theta_{cr}$ is as follows:

$$
\cos \theta_{cr} = \sqrt{\frac{\gamma+1}{4}} \left( 1 - \exp \left( -2.3 \frac{\Delta P}{\rho_0} \right) \right)
$$

(16)

When the shock wave is superposed and propagated into the explosive, the reflection and transmission will occur on the explosive surface, since the wave impedance of the air is less than the baffle wave impedance, the compressed wave will be reflected in the air and transmitted in the explosive. According to the continuous interface condition and Newton's third law, the velocity and pressure of the particles on both sides of the interface after reflection and transmission are equal, thus:

$$
P_e = TP_d
$$

(17)

$$
n = \frac{\rho_e c_0_1}{\rho_e c_0_2} \quad T = \frac{2}{1+n}
$$

(18)

In the above formula, $n$ is the acoustic impedance ratio of the two media, $T$ is the transmission coefficient, $P_e$ is the pressure on the explosive surface. Since the acoustic impedance of air is far less than that of explosives, $n$ in the equation tends to infinity, then $T = 2$, which is equivalent to the reflection of elastic wave on the rigid wall.

3. Numerical simulation Study on Shock Initiation of the Charge Covered by Metal Plate with Penetrated Notch

3.1. Calculation model
In order to study the shock initiation process with the charge covered by metal plate with defects, the nonlinear finite element program AUTODYN-2D is used to simulate the shock initiation of the charge covered by steel plate with penetrated notch. The finite element calculation model is an axisymmetric structure, as shown in figure 3. The calculation model includes: donor charge, defective covered plate, acceptor charge and air domain. Both the donor and the acceptor charge are cylindrical pressed TNT with the same diameter 35mm and height 30mm, the thickness of the covered plate is 3mm, and the upper and lower sizes of the notch are different. The numerical calculation uses a pure Euler algorithm, and the initiation point is set at the center point of the donor charge surface.

![Figure 3](image_url)

Figure 3. Numerical calculation model of the shock initiation with defective covered charge.
3.2. Material model
The air domain adopts the unbiased stress dynamic model (Null) and the Linear Polynomial equation of state [12]. The donor charge is the HIGH-EXPLOSIVE_BURN constitutive model and the JWL equation of state. The JWL equation of state is as follows:

\[ P = A(1 - \frac{\omega}{R_1^p})e^{-\frac{R_1}{V}} + B(1 - \frac{\omega}{R_2^p})e^{-\frac{R_2}{V}} + \frac{\omega E}{V} \]  

(19)

Where P is the pressure of detonation products, V is the hematocrit of unit volume, E is the initial internal energy, \( \omega \), A, B, R_1 and R_2 are constants.

The covered plate material model uses the Johnson-Cook model and the Grüneisen equation of state. The specific material parameters of the covered plate and the donor charge are shown in Table 1.

**Table 1. Parameters for donor charge and shell model [13-15].**

| Explosive materials | \( \rho_0 \) /g·cm\(^{-3}\) | \( P_{c-J} \) /GPa | \( A/GPa \) | \( B/GPa \) | \( R_1 \) | \( R_2 \) | \( \omega \) | \( E \) |
|---------------------|-----------------|-----------------|--------|--------|------|------|------|------|
| TNT                 | 1.60            | 6812            | 18.56  | 3.7    | 0.0323 | 4.15 | 0.95 | 0.3   | 0.07 |
| Shell materials     | \( \rho_0 \) /g·cm\(^{-3}\) | \( G/GPa \) | \( A/GPa \) | \( B/GPa \) | \( C \) | \( n \) | \( m \) | \( T_m/K \) | \( T_r/K \) |
| 45#steel            | 7.85            | 82.3            | 0.507  | 0.320  | 0.28  | 0.064 | 1.06 | 1765  | 298  |

The Ignition and Growth reactive (I&G) model was used to describe the Pressed-TNT explosive detonation. The parameters for Ignition and Growth reactive model for Pressed-TNT explosives were listed in Table 2.

The reaction rate equation in Ignition and Growth model is of the form:

\[ \frac{d\lambda}{dt} = I(1 - \lambda)^b(\frac{\rho}{\rho_0} - 1 - \alpha)^c + G_1(1 - \lambda)^dP^e + G_2(1 - \lambda)^fP^g \]  

(20)

Where \( \lambda \) is the reacted fraction, \( t \) is time, \( \rho \) is current density, \( \rho_0 \) is initial density, \( P \) is pressure, and \( I \), \( b \), \( a \), \( x \), \( G_1 \), \( c \), \( d \), \( y \), \( G_2 \), \( e \), \( g \), \( z \) are constants.

**Table 2. Ignition and Growth reactive flow model parameters for TNT [15].**

| \( I \) /use\(^{-1}\) | \( G_1 \) /100GPa | \( G_2 \) /100GPa | a | b | c | d | e | g | x | y | z |
|---------------- |------------------|------------------|---|---|---|---|---|---|---|---|---|
| 8e8            | 420              | 260              | 0.111 | 0.667 | 0.667 | 0.667 | 0.333 | 1 | 6 | 3 | 3 |

4. Test verification
In order to analyze the effectiveness of the numerical simulation, a verification test is carried out by taking the shock initiation of the covered charge as an example, and the critical covered plate thickness of TNT during contact explosion and the sympathetic detonation distance of covered pressed TNT during non-contact explosion were acquired. Figure 4 shows the physical picture of the shock initiation on the covered charge and the axisymmetric numerical calculation model. We carried out the shock initiation of covered charge tests seven times, and among them three times were contact explosion tests. The test device consists of detonator, booster, donor charge, 45 # steel covered plate, acceptor charge and witness plate. The donor charge of the contact explosion test is in direct contact with the 45# steel covered plate. The thickness of the covered plate corresponding to the three contact explosion tests is 20, 23 and 26mm respectively. There are four non-contact explosion tests, and the test device has one more PPR sleeve than the contact explosion test device, which is used to separate the donor charge from the 45 # steel covered plate. The height of PPR sleeve corresponding to four non-contact explosion tests is 10, 12, 15 and 19mm respectively, and the thickness of covered plate is 3mm. The donor charge and the acceptor charge in the test are both cylindrical pressed TNT with the same size, 35mm in diameter and 30mm in height. The booster is a cylindrical polyblack-14, which is placed directly above the donor charge, and is connected with a detonator to detonate the donor charge. The inner diameter of PPR sleeve is 33.7mm, the outer diameter is 40mm, the witness plate is Q235 steel, and the thickness is 20mm.
In the experiment, the detonator first initiates the detonator, and then initiates the donor charge. The shock wave generated by TNT explosion of the donor charge directly attenuates through 45# steel covered plate and acts on the acceptor charge in the contact explosion test. The difference of the non-contact explosion test is that the shock wave generated by the explosion of the donor charge is attenuated by air and 45 # steel covered plate respectively and then acts on the TNT.

Table 3 shows experimental and numerical simulation results of the shock initiation of the covered charge with different thickness of covered plate and different detonation distances. As shown in table 3, the critical thickness of the covered plate is between 20 and 23 mm for the pressed TNT ignited by contact explosion, and the critical thickness of the covered plate by numerical simulation of contact explosion is 23mm. The error between the numerical simulation results and the test results is less than 13.1%. The sympathetic detonation distance of the covered-pressed TNT in non-contact explosion ranges from 12-15 mm, and the critical sympathetic detonation distance calculated by numerical simulation of non-contact explosion is 14mm. The error between the numerical simulation results and the test results is less than 14.3%. The numerical simulation results are well accord with the test results.

**Table 3.** Test and simulation results of shock initiation of covered charge.

| Contact explosion | Test results | Simulation results |
|-------------------|--------------|--------------------|
| The thickness of the covered plate /mm | Explosion situation of acceptor charge | The thickness of the covered plate /mm | Explosion situation of acceptor charge |
| 20 | exploded | 23 | exploded |
| 23 | unexploded | 23.5 | unexploded |
| Non-contact explosion | Test results | Simulation results |
| Sleeve height /mm | Explosion situation of acceptor charge | Sleeve height /mm | Explosion situation of acceptor charge |
| 12 | Part of the explosion | 14 | exploded |
| 15 | unexploded | 14.5 | unexploded |

![Figure 4](image.jpg) **Figure 4.** The picture of the shock initiation on the covered charge and the numerical model.
Figure 5. Witness plate deformation comparison chart of the experiment and numerical simulation.

The witness plate deformation comparison chart of the experiment and numerical simulation at 12mm interval is shown in figure 5. After the acceptor charge is exploded, the pit depth of Q235 witness plate obtained by numerical calculation is 4.3mm and the pit diameter is 43.0mm. The test results show that the pit depth is 4.20mm and the diameter is 40.0mm. The error between the numerical simulation and the test results of the witness plate pit depth is no more than 2.38%. The error between the numerical simulation and the experimental results of the diameter of the witness plate is not more than 7.50%. The numerical simulation results agree well with the experimental results.

5. Analysis and discussion

5.1. Comparison of theoretical and simulation results

The theoretical calculation model is shown in figure 1. The mass of the donor charge TNT is 0.047kg, the equivalent radius is 2.24cm, and the distance between the donor charge and the covered plate is h. After the charge exploded, the pressure at different points in the notch was tested by Gaussian point. The comparison between the calculated values of the above theoretical model and the simulation results is shown in table 4. Keep the diameter of the lower notch unchanged, change the slope of the covered plate by adjusting the diameter of the upper notch, and analyze the influence of the covered charge on the detonation under six different working conditions. Compare the pressure of reflection and superposition in numerical simulation with theoretical calculations. The maximum error between the attenuation pressure and theoretical value is 11.55%, the maximum error between the reflection pressure and the theoretical value is 7.45%, and the maximum error between the superimposed shock wave pressure and theoretical value is 17.43%. The theoretical calculation results and the numerical simulation results agree with each other well.

Table 4. Comparison of theoretical models and simulation results.

| Gradient (°) | Detonation distance (cm) | Attenuated pressure P₁(MPa) Theoretical results | Reflective pressure P₂(MPa) Theoretical results | Superimposed pressure P₆(MPa) Simulation results | Explosive interface pressure Pe(MPa) Simulation results | Error of interface pressure (%) | Reaction time(us) Simulation |
|-------------|--------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------|------------------------------|
| 10          | 10                       | 10.72                                         | 12.12                                         | 78.3 4                                        | 86.54                                        | 240.89                       | 270.74                       |
| 20          | 10                       | 10.72                                         | 12.12                                         | 70.65                                         | 74.13                                        | 216.68                       | 250.44                       |
| 30          | 10                       | 10.72                                         | 12.12                                         | 58.70                                         | 62.68                                        | 177.35                       | 206.87                       |
In order to verify the correctness of the theoretical model and the numerical simulation results, the critical criteria for the shock initiation of the heterogeneous explosives were introduced. Shock initiation is a dynamic response form of explosive to pressure pulse. At present, the dynamic response of explosives to impact loads is divided into two cases: one is the impact shock detonation (SDT) under strong impact load, the other is the reverse (LALDS) of long continuous pulse time.

Under the action of strong shock wave loading, the explosive detonation criterion can be expressed as:

\[ p^2 \tau = K \]  \hspace{1cm} (21)  

Where \( p \) is the shock wave pressure at the interface of the explosive, \( \tau \) is the time of the shock to detonation, and \( K \) is the parameter related to the explosive.

When the explosive interface pressure \( p \) is lower than the critical initiation pressure \( p_c \), the long-term low-pressure shock wave continues to act to form a detonation of the explosive. In this case, the explosive detonation criterion can be expressed as:

\[ p^n \tau = K \]  \hspace{1cm} (22)  

From the shock initiation criterion, each of the specific charge has a critical initiation characteristic parameter. That is the critical initiation pressure \( p_c \), the energy coefficient \( K \) and the empirical constant \( n \).

Since the pressure transmitted into the explosive does not reach the critical detonation pressure, the explosive takes a relatively long time to detonate under the action of the low pressure shock wave, so the second form of the shock initiation criterion \( p^2 \tau = K \) is adopted. The detonation characteristics of the charge are described by parameters \( n, K \). Using the data in table 3, fitting by least squares method yields \( n=2.12, K=1.24\times10^2 \) (International System of Units) is obtained. Therefore, using the theoretical simplified model and the obtained shock initiation criterion by fitting, the detonation characteristics of the acceptor explosive under the action of the airborne shock wave can be well described in a certain range.

5.2. Analysis of shock initiation process of the charge covered by metal plate with defects

In order to study the shock initiation process of the charge covered by metal plate with defects, the covered plate with the upper and lower notch diameters of 7 mm and 1mm, 4 mm and 1mm respectively is taken as an example to analyze the detonation growth process and the incomplete detonation process of the acceptor charge. Figure 6 shows a cloud chart of typical explosion pressure at different times of the acceptor charge on shock initiation when the upper and lower notch diameters of the covered plate is 7 mm and 1 mm at a height of 40 mm. As shown in figure 6, the initial donor charge is detonated, and the shock wave reaches the surface of the covered plate notch at t=13us. It is obvious that the shock wave superposition occurs on the upper surface of the acceptor charge at the notch, and the pressure of the covered plate reached 502 MPa. After 5 us time in the acceptor charge, the shock wave reaches the critical initiation energy value of the charge and will be detonated by the charge, forming a wave front with strong pressure and spreading rapidly to the inner layer of the explosive. After 22us, the charge is completely detonated, and the detonation pressure reached 21.2GPa. Figure 7 shows a cloud chart of typical explosion pressure at different times of the acceptor charge on shock initiation when the upper and lower notch diameters of the covered plate is 4 mm and 1 mm at a height of 40 mm. As shown in figure 7. The shock wave reaches the surface of the acceptor charge at t=13us, and the notch of the covered plate is superimposed. But the pressure of the covered plate only reaches 221MPa. After a few microseconds, the pressure of the charge is increased, but it fails to reach the critical initiation energy of the charge. When the time is 18us, the shock wave has flowed out from the non-reflective boundaries, and the acceptor charge was still has not exploded.
Figure 8 (a) shows gauges point distribution. Figure 8 (b) and (c) show complete detonation process and the incomplete detonation process of the acceptor charge when the upper and lower notch diameters of the covered plate is 7 mm and 1 mm, 4 mm and 1 mm at a height of 40 mm, respectively. Label 1-7 in the figure is the marked position of the acceptor charge from bottom to top. It can be seen from the comparison of figure 8 (b) and (c) that when the upper and lower notch diameters of the covered plate is 7 mm and 1 mm. After the pressure on the surface of the acceptor charge reaches 502MPa under the shock wave, the explosive starts to react to increase the pressure instantaneously, and the highest pressure reaches 3.6GPa. The maximum pressure reached 21.2 GPa at a distance of 12 mm from the surface of the acceptor charge with the growth of detonation, and it is basically stable at the later distance, reaching a stable detonation state. When the upper and lower notch diameters of the covered plate is 4 mm and 1 mm, the pressure on the surface of the acceptor charge reaches 221 MPa under the shock wave. And after a few microseconds, the pressure of the acceptor charge is raised to 1.56GPa. However, the acceptor charge do not react. Due to the combined effect of lateral and axial rarefaction waves, the pressure gradually decreased with the increase of the propagation depth, and the acceptor charge could not exploded.

Figure 6. Cloud chart of the acceptor charge on shock initiation when the upper and lower notch diameters of the covered plate is 7 mm and 1 mm at a height of 40 mm.

Figure 7. Cloud chart of the acceptor charge on shock initiation when the upper and lower notch diameters of the covered plate is 4 mm and 1 mm at a height of 40 mm.
5.3. Influence of different notch sizes of covered plate on shock initiation by acceptor charge
Because the different sizes of the upper and lower diameters of the covered plate play a key role in the reflection and superposition of shock waves, it is necessary to study the influence of the notch size of the covered plate on the impact of the covered charge. Based on the correctness of the above numerical simulation, the shock initiation of the charge covered by metal plate with defects is simulated numerically by changing the sizes of the upper and lower notches. The simulation calculation results of the sympathetic detonation distance of the covered charge with different notch size are shown in Table 5. For the pressed TNT with and without 45# steel covered plate with the thickness 3 millimeters, the critical detonation distance of non-contact explosion was 13 millimeters and 81 millimeters, respectively. For the covered plate with a cylindrical notch, the critical detonation distance of the pressed TNT increases with increase of the diameter of the covered plate. For the covered plate has a frustum notch, in normal reflection ($\alpha_0 < 70^\circ$), the critical detonation distance of the pressed TNT decreases with increase of the slope.

Table 5. Simulation results of the detonation distance of the covered charge with different notch size.

| Serial number | Thickness of the covered plate (mm) | Upper notch diameters /mm | Lower notch diameters (mm) | Gradient ($^\circ$) | Detonation distance (mm) |
|---------------|------------------------------------|---------------------------|---------------------------|--------------------|-------------------------|
| 1             | 3                                  | 0                         | 0                         | /                  | 13                      |
| 2             | 3                                  | 10                        | 1                         | 33.7               | 59                      |
| 3             | 3                                  | 7                         | 1                         | 45                 | 51                      |
| 4             | 3                                  | 4                         | 1                         | 63.5               | 38                      |
| 5             | 3                                  | 1                         | 1                         | 90                 | 36                      |
| 6             | 3                                  | 4                         | 4                         | 90                 | 45                      |
| 7             | 0                                  | /                         | /                         | /                  | 81                      |

6. Conclusions
In this paper, a theoretical model of the shock initiation of the charge covered by steel plate with penetrated notch was established. The theoretical calculation model was verified by the numerical simulation results. The nonlinear finite element program was used to simulate the shock initiation
process of pressed charge, and the validity of the numerical simulation was verified by experimental results. The following conclusions can be drawn from the current study:

1) The critical thickness of the covered plate is between 20 and 23 mm for the pressed TNT ignited by contact explosion, and the critical thickness of the covered plate by numerical simulation of contact explosion is 23 mm. The error between the numerical simulation results and the test results is less than 13.1%. The sympathetic detonation distance of the covered-pressed TNT in non-contact explosion ranges from 12-15 mm when the thickness of the 45 steel covered plate is 3 mm, and the critical sympathetic detonation distance calculated by numerical simulation of non-contact explosion is 14 mm. The error between the numerical simulation results and the test results is less than 14.3%. When the critical thickness of the covered plate and the critical initiation distance and the deformation of the witness plate are taken as the comparison parameters, the numerical simulation results accord well with the experimental results. It shows that the calculation model can effectively describe the shock initiation test of the covered charge by using ALE algorithm.

2) The parameters \( n \) and \( K \) of the critical initiation criterion were obtained by least squares method, and the theoretical model can better describe the detonation characteristics of the covered charge under the near-field explosion shock wave, which provides a theoretical reference for shock initiation experiments and subsequent reliability studies.

3) For the pressed TNT with and without 45# steel covered plate with the thickness 3 millimeters, the critical detonation distance of non-contact explosion was 13 millimeters and 81 millimeters, respectively. For the covered plate with a cylindrical notch, the critical detonation distance of the pressed TNT increases with increase of the diameter of the covered plate. For the covered plate has a frustum notch, the critical detonation distance of the pressed TNT decreases with increase of the slope in normal reflection. The critical detonation distance of the pressed TNT decreases with increase of the slope.

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