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Study on Overdriven Detonation of Double-Layer Shaped Charge

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Abstract: Overdriven detonation(ODD) means that the detonation process of explosives no longer follows the C–J detonation process and its detonation parameters are larger than the C–J values. ODD is an unstable detonation process. With the increasing of propagation distance, detonation parameters tend to C–J value gradually. The double-layer shaped charge (DLSC) with high detonation velocity explosive (HE) in the outer layer and low detonation velocity explosive (LE) in the inner layer can keep the axis of shaped charge in the ODD state all the time. The paper derived formulas for calculating the parameters of overdriven detonation when the HE detonates the LE. Based on the conservation of momentum, mass and energy, the functional relationship between the intensity of Mach wave and the incident angle of the detonation wave in the shaped charge is deduced. Study on the propagation law of detonation waves in DLSC with the wave shaper by numerical simulation. The results show that the peak value of Mach wave pressure in DLSC is not increased compared with that in ordinary shaped charge (OSC), but the attenuation speed of Mach wave pressure can be delayed and ultimately in the ODD state. The final parameters of the ODD state are determined by the detonation velocity and the polytropic exponent of the explosive. The results of numerical simulation are consistent with theoretical calculation, which confirms the accuracy of the formulas.

Keywords: overdriven detonation · detonation wave · double-layer shaped charge · wave shaper · mach wave

1 Introduction

Double-layer shaped charge (DLSC) consists of two kinds of detonation velocity explosives, the outer charge adopts high detonation velocity explosive (HE) and the inner charge adopts low detonation velocity explosive (LE). The axis of DLSC can always keep in the state of ODD. The function of wave shaper in shaped charge is mainly to control the detonation waveform and obtain the ideal detonation waveform matching the liner. The DLSC with the wave shaper improves the detonation wave pressure, changes the incident angle of the detonation wave on the liner and improves the energy utilization ratio of the shaped charge. The ODD caused by the DLSC has broad application prospects. Scholars in various fields have studied the performance of the DLSC. However, the existing research on the principle of ODD in DLSC is not very clear.

Altshuler first observed the ODD state in B explosives. Through special experimental test methods, the detonation wave with a detonation velocity of 2 times C–J detonation velocity and a detonation pressure of 120Gpa was obtained [1]; H. Kato proposed the application of the overdriven detonation technology to the shaped charge in the International Symposium on Ballistics [2]; J. N. Fritz pointed out that in most engineering systems, due to the existence of boundary conditions and reflection effects, the state of explosive detonation wave deviates from the main isentropic and the detonation wave pressure will be higher than CJ value, the interaction between detonation waves can also produce overpressure [3]; The Los Alamos National Laboratory's research report gives the pressure and sound velocity of the ODD Hugoniot of two PBX explosives, it is also proposed to numerically simulate the ODD process by adding an equation to the standard JWL equation [4]; The Kumamoto University Materials Impact Dynamics Laboratory has made a series of advances in the theoretical analysis, numerical simulation and experimental research of the ODD [5–7].

Since the 1970s, through experimental research many scholars have confirmed that the detonation waves in the shaped charge with wave shaper collide with each other can form Mach waves [8]; Tang used high-speed photography to measure the Mach wave formed in the shaped charge, the detonation speed reached 1.9 times of the C–J value and the detonation pressure reached 3 times of the C–J value [9]; Yang established a theoretical formula for the interaction of detonation waves in shaped charge with the wave shaper according to the Whitham method [10]; Pan pointed out that the critical incident angle of the Mach reflection caused by the detonation wave depends on the polytropic exponent of the explosives and the formula for

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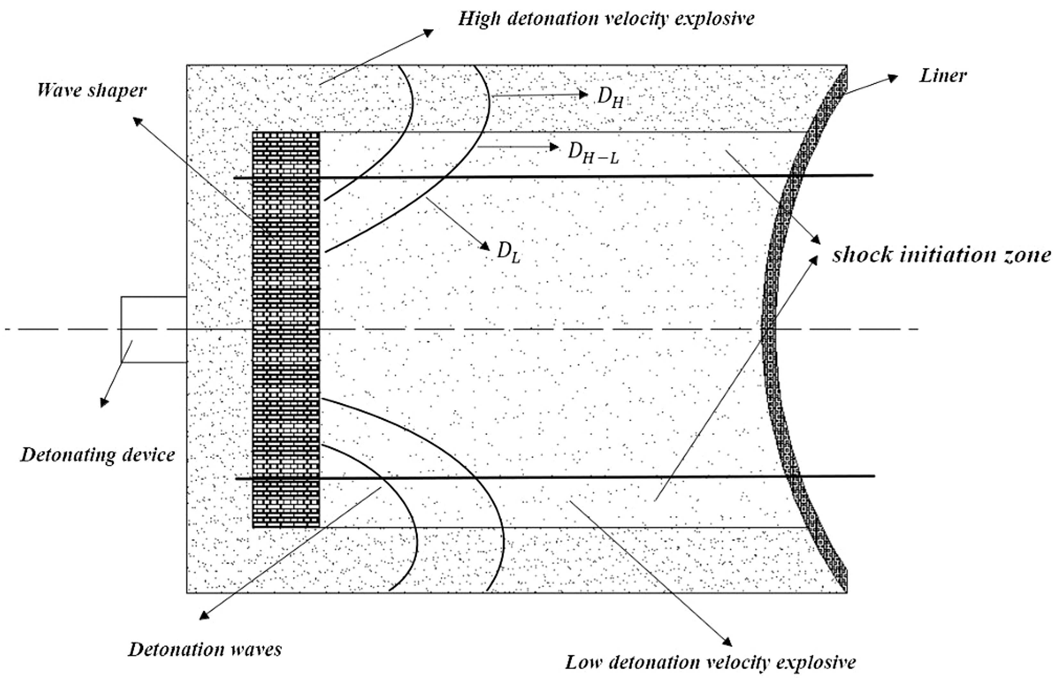


Figure 1. Detonation wave propagation of DLSC

calculating the pressure and height of the Mach stem was given [11].

Regarding the study of DLSC, Held used a stripe mirror camera to measure the detonation process of the DLSC with the inner layer is TNT, glass, HMX/binder (85/15) and the outer charge is TNT/HMX (15/85). The results show that the DLSC will form a convergent arc detonation wave[12]. Louis Zernow placed sensors at a distance from the explosive to obtain the directional effect of detonation wave. The results show that the detonation product velocity of DLSC is 1350–1500 m/s higher than that ring initiation and the directional detonation performance of DLSC is obviously improved [13]. Many scholars have discussed the application of the DLSC. The research shows that the jet velocity, jet kinetic energy and penetration depth are greatly improved in the DLSC compared with the ordinary shaped charge [14]. Zhang analyzed the propagation process of detonation waves in DLSC and gave a calculation model of Mach stem height based on the conservation of Mass [15]. In the 26th International Symposium on Ballistics, TDW Company of Germany proposed that the PELE/EFP multimode damage element was obtained by using the DLSC with wave shaper and the feasibility of the scheme was studied through experiments, but related molding mechanism has not been elaborated [16].

Based on the above background, the paper compares and analyzes the propagation law of detonation waves in ordinary shaped charge(OSC) and DLSC with the wave shaper. The paper derived formulas for calculating the parameters of ODD when the HE detonates the LE. Based on the conservation of momentum, mass and energy, the functional relationship between the intensity of Mach wave and incident angle of detonation wave in shaped charge is deduced. The accuracy of the obtained formula was verified by the combination of theoretical analysis and numerical simulation. The research results can provide some reference value for the study and application of ODD mechanism of DLSC.

1.1 ODD State on the Contact Surface of the two Explosives

As shown in Figure 1. In the DLSC, due to the difference in chemical and physical properties of the two explosives, when the detonation wave of the HE shock initiation the LE, the detonation wave propagating in the LE near the contact surface will gradually deviate from the C–J condition, the following contents analyze the ODD state near the contact surface of the HE and LE.

After the explosive is detonated, the propagation velocity of the detonation wave tends to the specific value of the explosive, that is, the idea detonation velocity D_{C-J}. Normally, the detonation wave will propagate stably with the ideal detonation velocity until the end of the detonation. In the C–J model, it is assumed that the detonation fluid is one-dimensional in the plane and the dissipation effect such as heat conduction is not considered. The detonation wave is a strong discontinuity surface and the chemical reaction heat Q is instantaneously released from the detonation wave chemical high-speed reaction zone. The detonation product in the state of thermochemical equilibrium and thermal equilibrium, the propagation of detonation waves is constant. During the propagation process of the detonation wave, the pressure P, the density ρ, the particle velocity u and the sound velocity c of the detonation wave are kept constant. The following equations are satisfied: (the subscript 0 indicates the initial state of the explosive and the subscript J indicates C–J status)

$$\begin{cases} P_J = \frac{\rho_0}{k+1} D_J{}^2; \rho_J = \frac{k+1}{k}\rho_0; u_J = \frac{1}{k+1} D_J \\ c_J = \frac{k}{k+1} D_J; D_J = \sqrt{2(k^2-1)Q} \end{cases} \tag{1}$$

k is the polytropic exponent of the explosive. In the C–J state, the velocity of the sparse wave after the wave front is equal to the propagation velocity of the detonation wave, that is, $u_J + c_J = D$. Under this condition, the sparse wave after the detonation wave cannot be transmitted to the detonation wave front and all the energy released by the reaction is used to support the steady propagation of the detonation wave.

The C–J theory regards detonation wave as an ideal strong discontinuity surface without thickness. In fact, no matter how fast the chemical reaction of detonation proceeds, it always takes a certain time and process to convert explosives into detonation products and release chemical energy. Therefore, detonation wave front must have a certain thickness. The Z–N–D model of detonation wave modifies C–J theory. Considering the limited chemical reaction rate, it is assumed that the detonation wave front has a certain thickness. The leading shock wave and the chemical high-speed reaction zone form the detonation wave front. They propagate forward at the same speed and separate the initial explosive from the detonation product, that is, a chemical high-speed reaction zone behind the detonation wave front.

As shown in Figure 2. (a). $N-N^{'}$ is the leading shock wave, $M-M^{'}$ is the end of the reaction, that is, C–J discontinuity surface.

The strong detonation process of the LE near the contact surface can describe with the Figure 2.(b). 1 is Hugoniot curve of detonation products and 2 is Hugoniot curve of explosives. Under normal detonation conditions, the explosive is subjected to shock wave, the explosive jumps from the initial state $O(p_0, v_0)$ to the point $N(p_N, v_N)$ state (Von Neumann spike), the temperature and pressure abrupt and the high-speed detonation chemical reaction is stimulated. With the release of reaction heat, the state decreases from N along Rayleigh line to C–J point of stable propagation of detonation products. For the ODD process, at the initial state point, the explosive is subjected to a strong shock wave above the N point, at which point the impact pressure reaches the high-pressure state OS point and then falls along the Rayleigh line to the ODD point.

The Haugoniot curve of detonation products can be expressed as follows: (e is the specific internal energy, v is the specific volume, the subscript 0 indicates initial state of the explosive)

$$e - e_0 = (P + P_0)(v_0 - v)/2 + Q \tag{2}$$

The Rayleigh line of detonation wave is as follows:

$$P - P_0 = \rho_0^2 D^2 (v_0 - v) \tag{3}$$

The detonation product of shaped charge is a mixture of polytropic gases. The movement of the detonation product is a polytropic process. The equation of state of the polytropic gases is as follows:

$$P = A(S)\rho^k \tag{4}$$

Because the steady propagation of detonation products is isentropic expansion, $A(S)$ is constant. According to the first law of thermodynamics:

$$TdS = de + Pdv,\ e = -\int P dv \tag{5}$$

Combining formula (5) and (4) to obtain the internal energy function:

$$\begin{aligned} e &= -\int A(S) v^{-k} dv = A(S)\frac{v^{1-k}}{k-1} + B(S) = A(S)\frac{\rho^k v}{k-1} \\ &+B(S) = \frac{Pv}{k-1} + B(S) \end{aligned} \tag{6}$$

In the internal energy function, $B(S)$ is the constant, substituting formula (6) for (2) and combining with Rayleigh line (3), eliminating the specific volume v:

$$\begin{aligned} &\frac{v_0^2(k+1)}{2D^2(k-1)}(P-P_0)^2 + \left(\frac{kp_0v_0}{D} - D\right)\frac{v_0}{(k-1)D} \\ &(P-P_0) + Q^{'} = 0 \end{aligned} \tag{7}$$

The above formula is about the quadratic equation of $(P - P_0)$, where $Q^{'} = Q - P_0 v_0/(k-1) + e_0 - B(S)$. The solution of the equation is as follows (8):

$$P - P_0 = \frac{D(k-1)}{v_0(k+1)}\left[\frac{\frac{D}{k-1} - \frac{P_0 v_0 k}{D(k-1)} \pm}{\sqrt{\left(\frac{D}{k-1} - \frac{P_0 v_0 k}{D(k-1)}\right)^2 - \frac{2(k+1)}{k-1}Q^{'}}}\right] \tag{8}$$

In the process of explosive detonation, $P \gg P_0$ and P_0 can be neglected. When the positive sign is taken before the radical sign, it corresponds to the strong detonation process [17], it can be obtained:

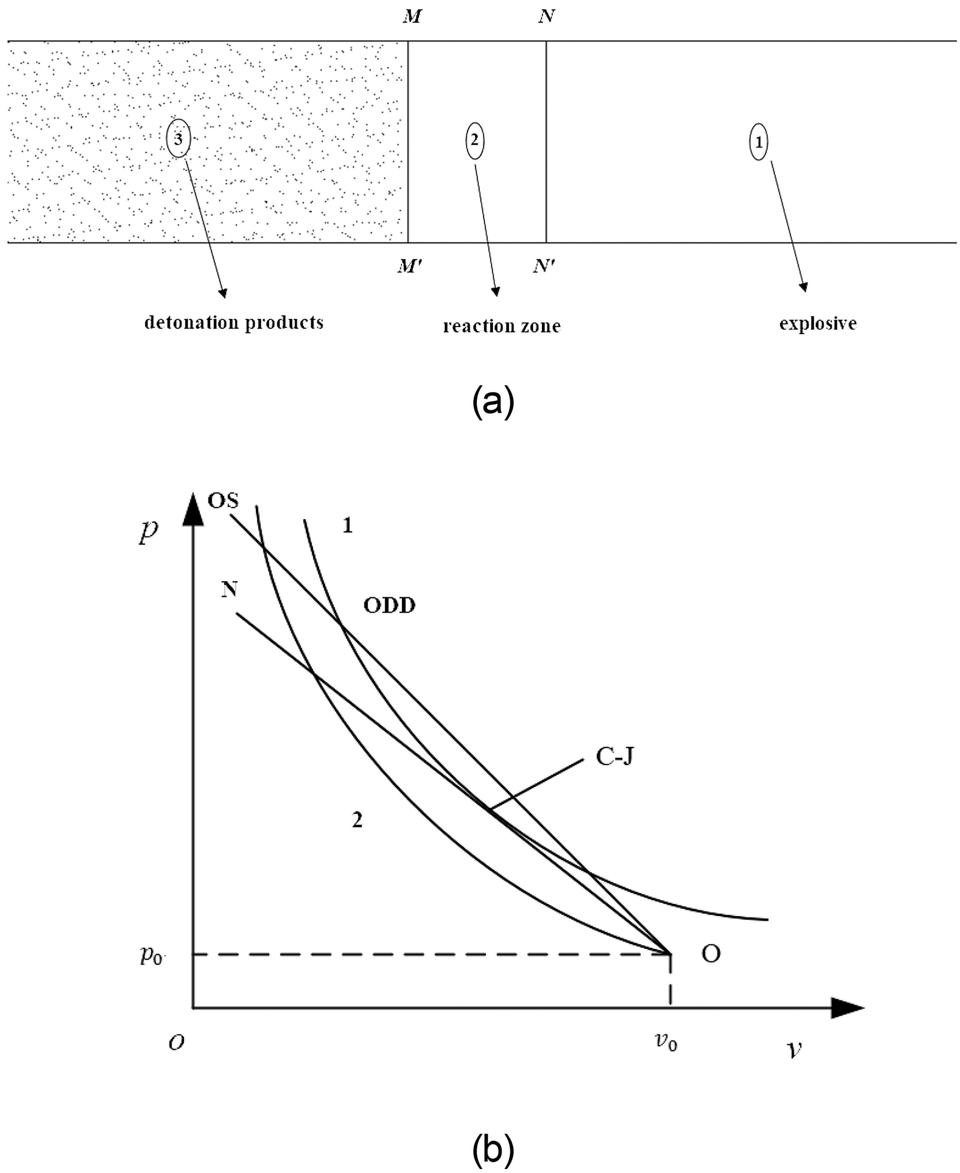


Figure 2. (a) Z–N–D model (b) Hugoniot curve

$$P = \frac{\rho_0 D^2}{k+1}\left[1 + \sqrt{1 - \left(\frac{D_J}{D}\right)^2}\right] \tag{9}$$

The letter m denotes the relationship between strong detonation and C–J detonation:

$$m = \sqrt{1 - \left(\frac{D_J}{D}\right)^2}, D = D_J/\sqrt{1 - m^2} \tag{10}$$

Substituting the formula (10) into (9) and (1) to obtain the pressure P, the density ρ, the particle velocity u and the sound velocity c on the detonation wavefront during strong detonation process. In order to facilitate the subsequent calculation, the formula is as follows:

$$\begin{aligned} P &= \frac{\rho_0 D^2}{k+1}(1+m) = \frac{\rho_0}{k+1}(1+m)\left(\frac{D_J}{\sqrt{1-m^2}}\right)^2 \\ &= \frac{\rho_0 {D_J}^2}{(k+1)(1-m)} = \frac{P_J}{1-m} \end{aligned} \tag{11}$$

$$\begin{aligned} u &= \frac{P}{\rho_0 D} = \frac{\rho_0 D^2}{\rho_0 D(k+1)}(1+m) = \frac{D}{k+1}(1+m) = \\ &\frac{1+m}{k+1}\left(\frac{D_J}{\sqrt{1-m^2}}\right) = u_J\sqrt{\frac{1+m}{1-m}} \end{aligned} \tag{12}$$

$$\rho=\rho_0\frac{D}{D-u}=\rho_0\frac{1}{1-u/D}=\rho_0\frac{1}{1-u_J(1+m)/D_J}=\rho_J\frac{1}{1-m/k} \tag{13}$$

$$c^2=kp/\rho=c_J^2\frac{1-m/k}{1-m} \tag{14}$$

The detonation product velocity of strong detonation is subsonic speed, that is, $D-u<c$. The sparse wave catches up with the detonation wave front and weakens the intensity of the detonation wave. Therefore, strong detonation is an unstable detonation process. The strong detonation process can be maintained only when the detonation product is propelled by a piston with a velocity greater than u_J.

When the detonation wave of HE propagates to LE, the particle velocity of HE is greater than the detonation products velocity of LE, that is, $u_H>u_L$. The dispersion of LE product is hindered. The detonation wave in LE is equivalent to a piston driving LE product forward at u_H velocity. The action of the piston will strengthen the detonation wave propagating in LE, which is larger than its normal detonation velocity D_L and produce ODD in the LE. The u_H and u_L are known constants of detonation product velocities of normal detonation. From formula (12), the relation of strong detonation parameters can be obtained.

$$u_H=u_L\sqrt{\frac{1+m}{1-m}} \tag{15}$$

Let m be expressed by the known characteristic constants u_H and u_L:

$$m=\frac{(u_H/u_L)^2-1}{(u_H/u_L)^2+1} \tag{16}$$

When the value of m is determined, according to the parameter relationships of the strong detonation, it can determine the ODD parameters near the contact surface of the two explosives. (k is the polytropic exponent of the LE)

$$\begin{cases} u_{H-L}=u_L \\ D_{H-L}=D_L\left(\frac{u_H}{u_L}+\frac{u_L}{u_H}\right)/2 \\ P_{H-L}=P_L[1+(u_H/u_L)^2]/2 \\ \rho_{H-L}=\frac{\rho_L k\left[1+(u_H/u_L)^2\right]}{(k-1)(u_H/u_L)^2+k+1} \\ c_{H-L}=c_L\sqrt{\frac{(k-1)(u_H/u_L)^2+k+1}{2k}} \end{cases} \tag{17}$$

2 Formation of Mach Wave at the Axis of Charge

In the DLSC with the wave shaper, the detonation wave interacts at the axis of charge, which can be regarded as the oblique incidence of the detonation wave on the rigid wall. When the incident angle of the detonation wave increases continuously, the irregular reflection occurs when the critical incident angle is reached and the Mach wave is formed. The parameters such as the pressure and density of the detonation product on the Mach wave front will be greatly increased, which will cause the explosive in the ODD state.

The continuous slip and reflection process of the detonation wave along the interface is an unsteady flow process. However, when the coordinate system is taken at the intersection of the incident detonation wave front and the rigid wall, only the state parameter changes near the collision point are studied, then a steady detonation wave action and a detonation product flow process can be seen. The physical schematic diagram is shown in Figure 3.

The image is divided into 4 regions, (0) is the original explosive, (1) is the detonation wave incident region, (2) is the reflection region and (3) is the Mach wave region. O is the collision point, $O^{'}$ is the tripe point, $O^{'}A$ is the incident detonation wave front and $O^{'}R$ is the reflection detonation wave front. $O^{'}O$ is the Mach stem, the chemical energy released by the Mach stem $Q^{'}_e$ is greater than the chemical energy Q_e released during C–J detonation, $O^{'}O$ is a curved surface, β is the angle between the tangent of each point on the Mach stem and the rigid wall. At O point, the wave front is perpendicular to the rigid wall, $\beta=90^{\circ}$, at $O^{'}$ point, $\beta=\varphi$. The oblique line $O^{'}f$ which separates the (2) region and the (3) region is a sliding line, the pressure on both sides of the line is continuous, that is, $p_2=p_3$, but the velocity is discontinuous, $q_2\neq q_3$. In the established coordinate system, the explosive passes through the incident detonation wavefront at a velocity $q_0=D/sin\varphi$ parallel to the rigid wall, then turns the angle θ and the flow velocity becomes q_1. The detonation product passes through the reflecting wavefront OR at the velocity of q_1 and turns the angle $\theta-\varepsilon$. If the $\theta-\varepsilon$ is greater than the maximum turning angle corresponding to q_1, the reflected wave that is push-

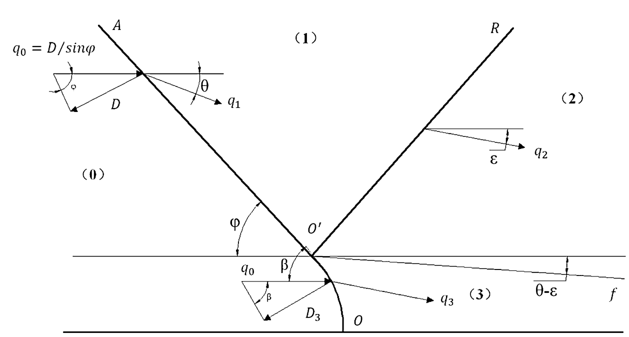


Figure 3. The diagram of mach reflection

ed away from the wall surface will be formed, that is, the Mach wave is generated. The explosives in the (0) region pass through the Mach wavefront to the (3) region and the velocity direction will also deflect. Between the curved surfaces O and $O^{'}$, the deflection angle changes from 0 to $\theta - \varepsilon$.

In order to obtain the pressure p_3 on Mach wavefront, the interface parameter equations are established to solve and deduce it. It can be seen from the geometric relationship in the Figure 3:

$$D_3 = q_0 sin\beta; q_0 = D/sin\varphi \tag{18}$$

Therefore, the velocity of Mach wave can be obtained:

$$D_3 = Dsin\beta/sin\varphi \tag{19}$$

From the conservation of momentum, the following results are obtained:

$$P_3 - P_0 = \rho_0(D_3 - u_0)(u_3 - u_0) \tag{20}$$

$$P_3 = \rho_0 D_3 u_3 = \rho_0 D_3^2 \frac{u_3}{D_3} \tag{21}$$

From the conservation of mass, it can be obtained:

$$\rho_0(D_3 - u_0) = \rho_3(D_3 - u_3) \tag{22}$$

$$\rho_0 D_3 = \rho_3(D_3 - u_3) \tag{23}$$

Formula (23) is transformed into:

$$u_3/D_3 = 1 - \rho_0/\rho_3 \tag{24}$$

Substituting formula (19) and (24) into (21), eliminating D_3 to obtain:

$$P_3 = \rho_0 \left(\frac{D}{sin\varphi} sin\beta\right)^2 \left(1 - \frac{\rho_0}{\rho_3}\right) \tag{25}$$

The pressure of detonation wavefront propagating steadily is P_J.

$$P_J = \frac{\rho_0}{k+1} D^2 \tag{26}$$

Dividing the two sides of equation (25) by (26) to obtain:

$$\frac{P_3}{P_J} = (k+1)\left(1 - \frac{\rho_0}{\rho_3}\right)\left(\frac{sin\beta}{sin\varphi}\right)^2 \tag{27}$$

When calculating the intensity of detonation wave at the axis of charge, that is, at O point, $\beta = \pi/2$, the formula is as follows:

$$\frac{P_3}{P_J} = (k+1)\left(1 - \frac{\rho_0}{\rho_3}\right)\left(\frac{1}{sin\varphi}\right)^2 \tag{28}$$

From the conservation of energy, it can be obtained:

$$e_3 - e_0 = \frac{1}{2}(P_3 + P_0)(v_0 - v_3) \tag{29}$$

The parameters of Mach wavefront are as follows:

$$\frac{P_3 v_3}{k-1} = \frac{1}{2} P_3(v_0 - v_3) + Q^{'}_e \tag{30}$$

In the formula above, $Q^{'}_e$ is the chemical energy released from the chemical reaction zone of Mach wave. Mach wave is an over-compressed detonation wave and the explosive is in the ODD state. The ratio of the chemical energy released by ODD to that released by normal detonation is expressed by the coefficient of overcompression ξ:

$$\xi = \frac{Q^{'}_e}{Q_e} \tag{31}$$

For the value of over-compression coefficient, refer to the reference [18]:

$$\xi = 0.8 + 0.2\left(\frac{sin\beta}{sin\varphi}\right)^2 \tag{32}$$

Under the condition of C–J detonation, the energy conservation equation is as follows:

$$\frac{P_J v_J}{k-1} = \frac{1}{2} P_J(v_0 - v_J) + Q_e \tag{33}$$

$$P_J = \frac{\rho_0}{k+1} D^2; v_J = \frac{k}{k+1} v_0 \tag{34}$$

Substituting formula (34) into formula (33) to obtain:

$$Q_e = \frac{P_J v_0}{2(k-1)} \tag{35}$$

The formulas (35) and (31) are substituted into (30) to obtain:

$$\frac{P_3 v_3}{k-1} - \frac{\xi P_J v_0}{2(k-1)} = \frac{1}{2} P_3(v_0 - v_3) \tag{36}$$

$$\frac{v_3}{v_0} = \frac{\rho_0}{\rho_3} = \frac{k-1}{k+1} + \frac{\xi}{k+1}\frac{P_J}{P_3} \tag{37}$$

The formula (37) is substituted into (27) to obtain:

$$\frac{P_3}{P_J} = (k+1)\left(1 - \frac{k-1}{k+1} - \frac{\xi}{k+1}\frac{P_J}{P_3}\right)\left(\frac{sin\beta}{sin\varphi}\right)^2 \quad (38)$$

$$\frac{P_3}{P_J} = \left(2 - \xi\frac{P_J}{P_3}\right)\left(\frac{sin\beta}{sin\varphi}\right)^2 \quad (39)$$

Let $\frac{P_3}{P_J} = n$ in formula (39) to solve the equation with n as an unknown number:

$$n^2\left(\frac{sin\varphi}{sin\beta}\right)^2 - 2n + \xi = 0 \quad (40)$$

$$n = \frac{P_3}{P_J} = \left(\frac{sin\beta}{sin\varphi}\right)^2 + \frac{sin\beta}{sin\varphi}\sqrt{\left(\frac{sin\beta}{sin\varphi}\right)^2 - \xi} \quad (41)$$

Substituting formula (32) into (41) to obtain:

$$\frac{P_3}{P_J} = \left(\frac{sin\beta}{sin\varphi}\right)^2 + \frac{sin\beta}{sin\varphi}\sqrt{0.8\left(\frac{sin\beta}{sin\varphi}\right)^2 - 0.8} \quad (42)$$

Formula (42) can be used to calculate the detonation pressure of Mach stem corresponding to the incident angle φ. When calculating the intensity of Mach wave at the axis of the charge, that is, O point, $\beta = \pi/2$, the function of Mach wave intensity at the axis of the charge with respect to the incident angle φ can be obtained:

$$\frac{P_3}{P_J} = \left(\frac{1}{sin\varphi}\right)^2 + \frac{1}{sin\varphi}\sqrt{0.8\left(\frac{1}{sin\varphi}\right)^2 - 0.8} \quad (43)$$

As shown in Figure 4, the curve of $\beta = 90°$is the curve of Mach wave intensity along the axis of charge with the incident angle of detonation wave. As shown in Figure 5, the curve is the mach wave intensity with incident angle of the mach stem.

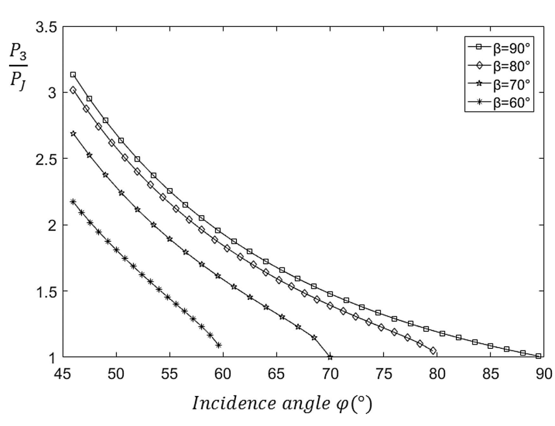


Figure 4. Mach Wave Intensity with Incident Angle

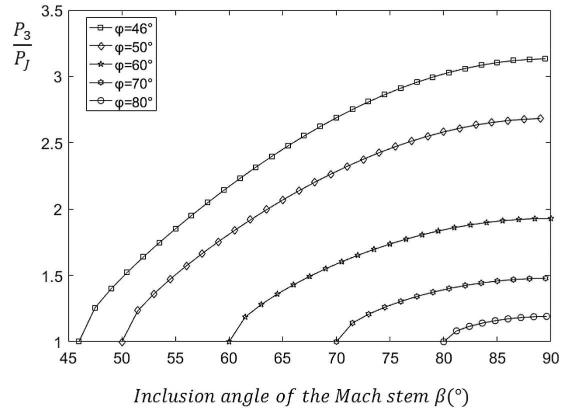


Figure 5. Mach Wave Intensity with Incident angle of the Mach stem

3 Numerical Simulation

3.1 Finite Element Calculation Model

The interaction process of detonation wave in DLSC with the wave shaper is analyzed. The detonation process of DLSC is numerically simulated by using the non-linear dynamics software Autodyn. The detonation process of explosive is a large deformation process of multi-material interaction. The Euler method can calculate the large deformation problem and deal with the multi-medium flow field of material interface and free surface.

3.2 Parameters of Numerical Simulation

The process of ODD is analyzed by numerical simulation. There are JWL and Lee-Tarver equation of state for explosives in Autodyn. Lee-Tarver equation is also called ignition growth model. The model includes two JWL equations, namely, one JWL equation of state for unreacted explosives and another JWL equation of state for detonation products. The JWL equation of state is expressed as:

$$P = A\left(1 - \frac{\omega}{R_1\eta}\right)e^{-R_1\eta} + B\left(1 - \frac{\omega}{R_2\eta}\right)e^{-R_2\eta} + \frac{\omega e}{\eta} \quad (44)$$

$$P_s = Ae^{-R_1\eta} + Be^{-R_2\eta} + C\eta^{-(\omega+1)} \quad (45)$$

In the formula, P is pressure and P_s is isentropic expansion pressure. ABC are the constants of the linear relationship between pressure and isentropic expansion pressure, $R1$ $R2$ and ω are the constants related to explosives. $\eta = \rho/\rho_0$, ρ_0 is the initial density of explosive, ρ is the density after detonation and e is the internal energy.

At the same time, the ignition growth model assumes that a small amount of explosives are ignited by shock heating and the reaction rate equation is controlled by the pressure and ignition surface area. Assuming that the incident shock wave is a plane shock, the reaction rate depends on the pressure. When the pressure in the explosive medium rises above the ignition threshold, the reaction begins. In the detonation simulation of the explosives, the pressure dependent the reaction rate is ubiquitous [19–20]. The reaction rate equation is as follows:

$$\frac{dF}{dt} = I(1-F)^b(\rho/\rho_0 - 1 - a)^x + G_1(1-F)^c F^d p^y + G_2(1-F)^e F^g p^z \tag{46}$$

In the formula, F is the degree of reactivity of explosive. It controls the release of chemical energy of explosive in the process of simulated detonation. When $F=0$, it means that the explosive has not reacted and when $F=1$, it means that the explosive has completely reacted. a denotes the critical compressibility and defines the ignition limit. When the critical compressibility is less than the critical compressibility, the explosive could not be ignited and detonation does not occur. y is the pressure index of combustion term, which is 1 in most cases. The burnup index of ignition and combustion terms $b=c=2/3$, representing the combustion of inward spherical particles. The parameters I and x control the number of ignition hot spots and the ignition term is a function of shock wave strength and pressure duration. G_1 and d control the reaction growth duration at the early stage of hot spots, that G_2 and z determine the reaction rate at high pressure. The first term of the ignition growth model represents the ignition of explosives under shock compression, the second term represents the growth of hot spots and the third term is mainly the relatively slow diffusion reaction. The HE is RDX and the LE is TNT, the JWL parameters are shown in Table 1, the reaction rate parameters are shown in Table 2.

Table 1. The JWL parameters.

Parameters	Unreacted explosive		Detonation products	
Explosive	TNT	RDX	TNT	RDX
$\rho/g \bullet cm^{-3}$	1.63	1.836		
$D/m \bullet s^{-1}$			6930	8239
A/Gpa	1798	2.01e+5	371.2	801.8
B/Gpa	-93.1	−0.05	3.23	52.64
R_1	6.2	12.4	4.15	5
R_2	3.1	1.24	0.95	2.1
ω	0.8926	0.8867	0.3	0.34

The wave shaper is nylon and the parameters of materials are as follows: Density is $\rho = 1.14 g/cm^3$, the Gruneisen coefficient is 0.87, the shear modulus is 3.68 Gpa, the yield limit is 0.05 Gpa.

The Lee-Tarver ignition growth model is used to describe the process of the ODD. JWL equation is used for HE in reference [15]. Now, we used the JWL equation and the Lee-Tarver equation for the HE of the DLSC respectively. The comparison results are shown in the Figure 7.

Table 2. The reaction rate parameters.

Parameters	TNT	RDX	Parameters	TNT	RDX
I	50	14	d	0	0.333
b	0.667	0.667	y	0	2
a	0.02	0.02	G_2	40	500
x	4	4	e	0.222	0.222
G_1	0	488	g	0.666	0.667
c	0.667	0.667	z	1.2	3

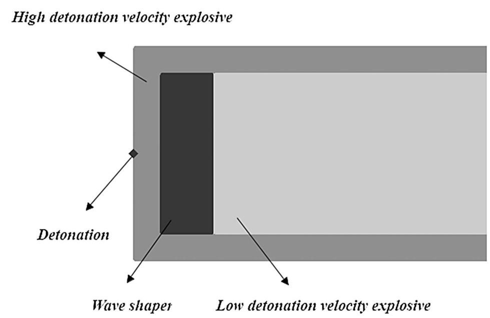


Figure 6. Finite element calculation model

It can be seen from Figure 7 that when the JWL equation is used for the HE, the detonation wavefront is discontinuous at the interface between the two explosive and there is a disconnection. Using the Lee-Tarver equation for the HE, the detonation wavefront is smooth and continuous. When the Mach wave propagates steadily, the shape of detonation wave varies greatly with different state equations. Analyzing the reasons, the JWL is a state equation with no chemical reaction and could not accurately describe the shock initiation process of HE to LE. As a result, the calculation results are quite different from the actual. Therefore, the HE should also use the Lee-Traver equation in numerical simulation. Considering that Lee-Traver equation of state could not be detonated directly by applying the initiation point in numerical simulation. So, the JWL equation is used for the auxiliary charge on the left side of the wave shaper and Lee-Traver equation is used for the main charge on the right side of the wave shaper.

4 Results and Discussion

The finite element model established in Figure 6 is used to simulate the propagation process of detonation wave in DLSC with the wave shaper. As shown in Figures 8–11, The propagation law of detonation wave in OSC and DLSC is compared and analyzed. And the shaped charge is divided into three cases: completely non separating explosion, incompletely separating explosion and completely separating explosion. Completely non separating explosion corre-

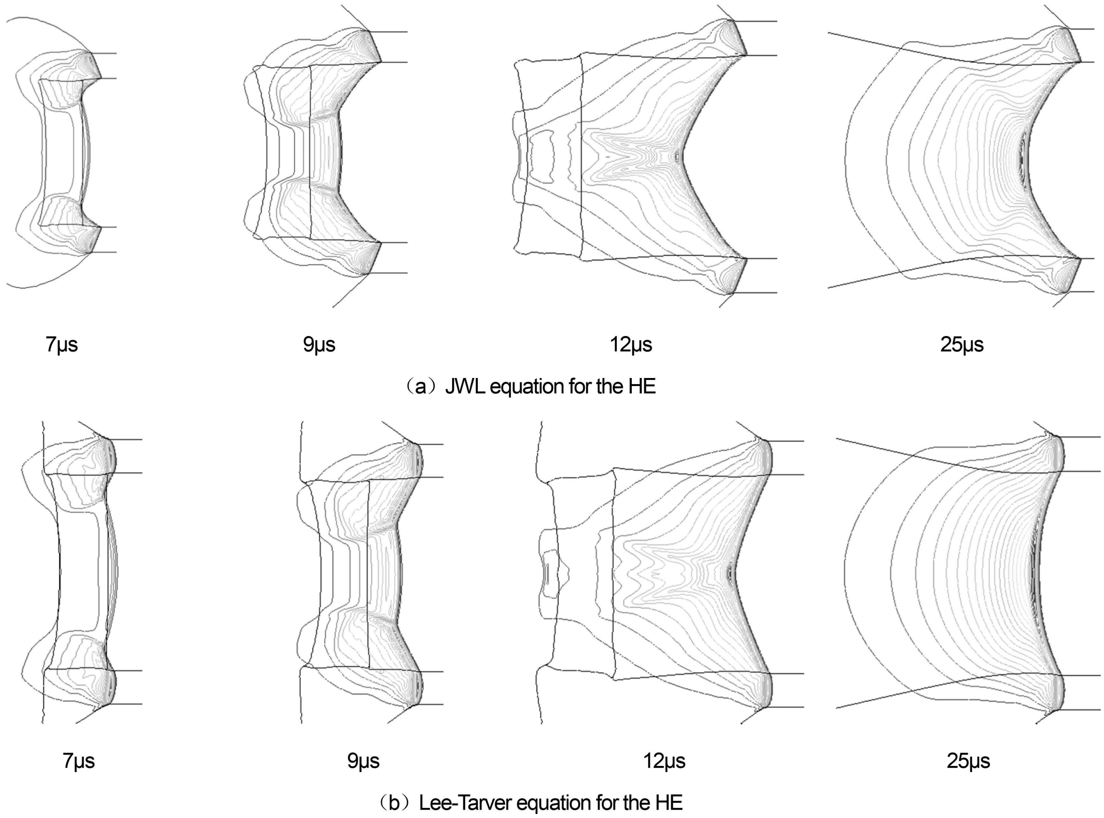


Figure 7. Comparison of numerical simulation of HE using different equation

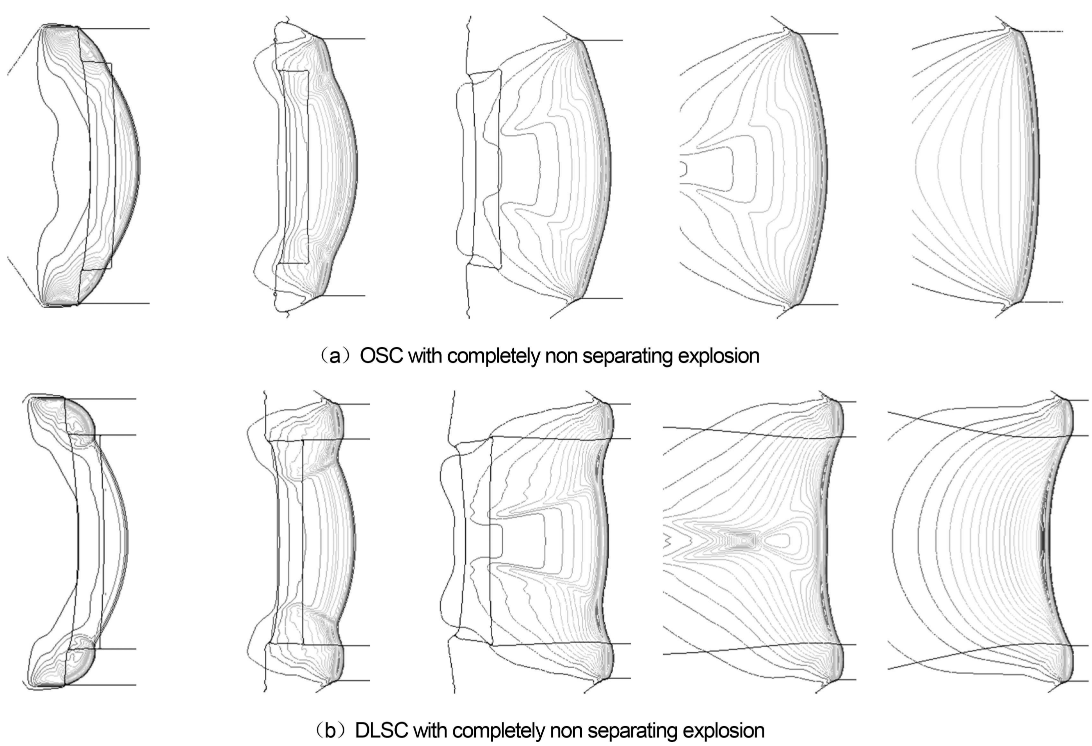
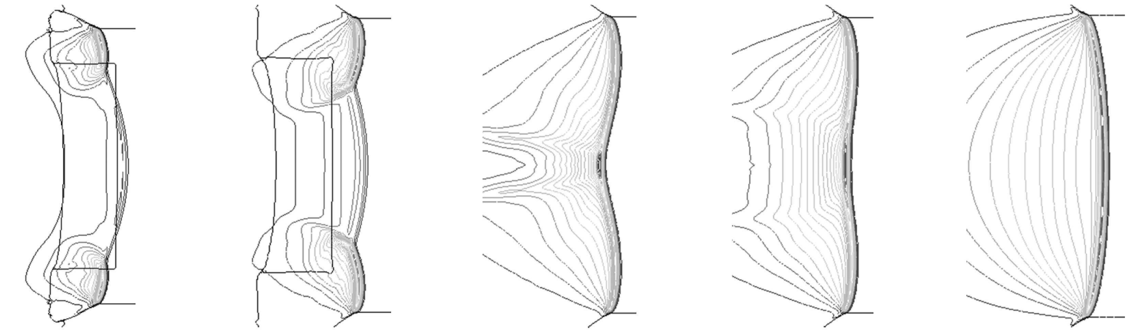
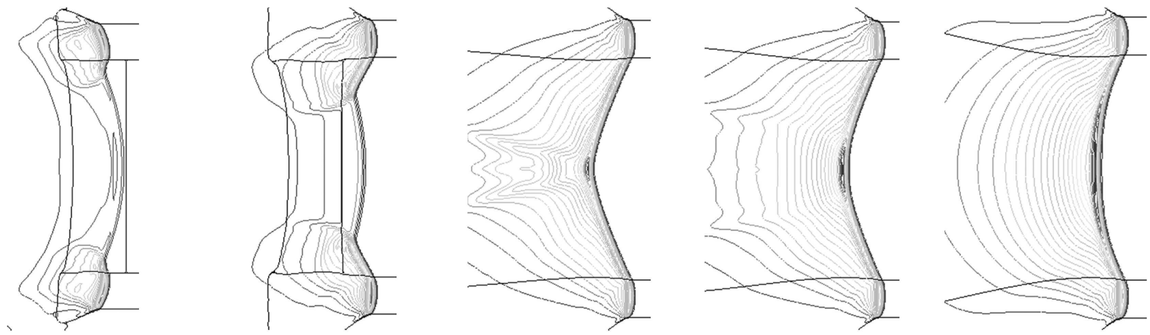


Figure 8. The thickness of the wave shaper is 10 mm

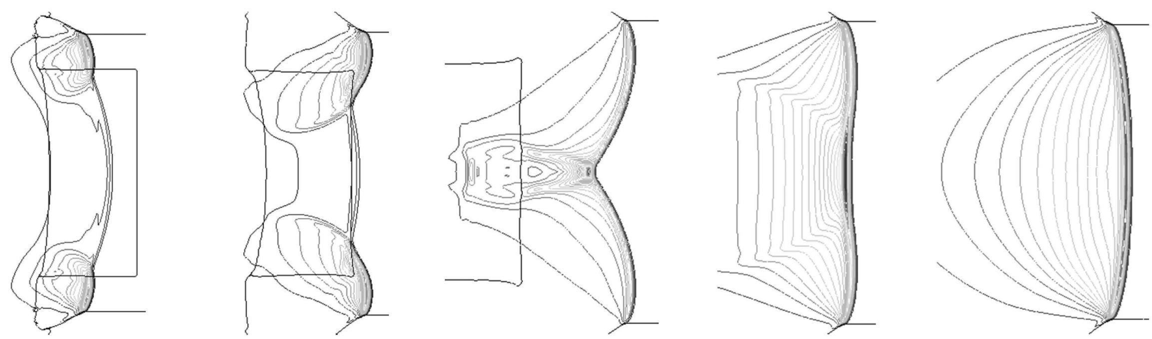


(a) OSC with incompletely separating explosion

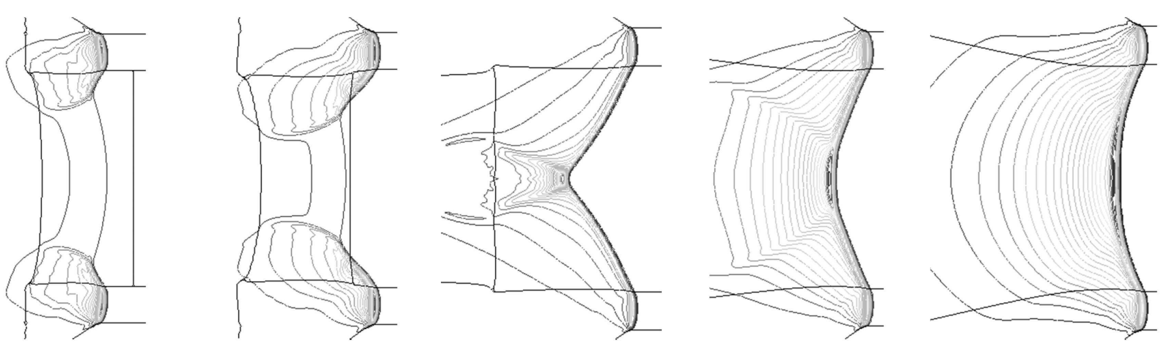


(b) DLSC with incompletely separating explosion

Figure 9. The thickness of the wave shaper is 20 mm

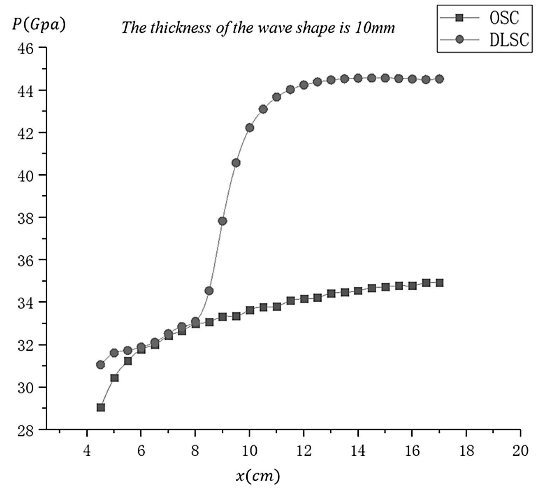


(a) OSC with completely separating explosion

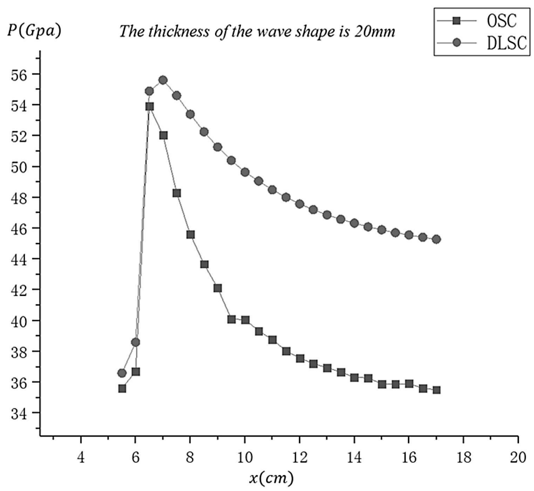


(b) DLSC with completely separating explosion

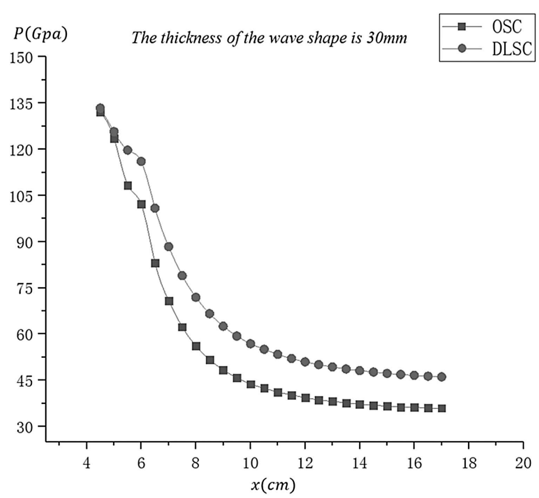
Figure 10. The thickness of the wave shaper is 30 mm



(a) The thickness of the wave shaper is 10 mm



(b) The thickness of the wave shaper is 20 mm



(c) The thickness of the wave shaper is 30 mm

Figure 11. The pressure curve of detonation wave at the axis of charge

sponds to the thickness of the wave shaper is 10 mm, incompletely separating explosion corresponds to the thickness of the wave shaper is 20 mm and completely separating explosion corresponds to the thickness of the wave shaper is 30 mm.

It can be seen from the above chart, in the OSC, the Mach wave can be formed at the axis of charge when the separating explosion performance of the wave shaper is better. However, with the increasing of propagation distance, Mach wave attenuates rapidly and eventually becomes spherical wave in the OSC. Under all kinds of separating explosion conditions, the DLSC can form Mach wave at the axis of the charge. The separating explosion performance of the wave shaper determines the initial incident angle of the detonation wave at the axis and then determines the peak pressure of the Mach wave. In the DLSC, When the detonation wave propagates steadily, it can maintain the ODD state and the detonation waveform is a convergent horn wave. Compared with the OSC, the peak value of Mach wave pressure in the DLSC is not increased, but the attenuation speed of Mach wave pressure can be delayed. The DLSC has obvious advantages when it is used in the shaped charge with large length-diameter ratio. In the numerical simulation, the pressure of detonation wave is $P_L = 35Gpa$ when the detonation wave propagates steadily in the OSC, $P_M = 44Gpa$ when the Mach wave propagates steadily in the DLSC and the intensity of Mach wave is $P_M/P_L = 1.25$. The intensity of detonation wave is calculated when Mach wave propagates steadily at the axis of the DLSC. The formulas deduced above are used to calculate the intensity of detonation wave.

$$\frac{P_M}{P_L} = \left(\frac{1}{sin\varphi}\right)^2 + \frac{1}{sin\varphi}\sqrt{0.8\left(\frac{1}{sin\varphi}\right)^2 - 0.8} \tag{47}$$

According to the references [15] and [21], the incident angle φ of detonation wave in the formula above is considered to be $\boldsymbol{sin}\varphi = D_L/D_H$. However, in this paper, the strong impact effect of the HE on the LE is considered. The formula is modified by $u = D/(k+1)$ combination formula (17):

$$\boldsymbol{sin}\varphi = \frac{D_L}{D_{H-L}} = 2/\left[\frac{D_H(k_L+1)}{D_L(k_H+1)} + \frac{D_L(k_H+1)}{D_H(k_L+1)}\right] \tag{48}$$

It can be seen from the formula that the Mach wave intensity of detonation wave propagating steadily in DLSC is determined by the detonation velocity and the polytropic exponent of the explosive. Using the method of theoretical analysis and numerical simulation, the LE is taken as TNT, the parameters are taken from reference [11] and the HE is Comp B, RDX, Octol and PBX9404 respectively. The results are compared as shown in Table 3. P_L is the normal propagating detonation wave pressure of the LE and P_M is Mach wave pressure.

Table 3. Comparison of theoretical calculation and numerical simulation when the LE is TNT.

Explosive	$\rho_0(g/cm^3)$	$D(m/s)$	k	$\varphi(^\circ)$ calculation	simulation	P_M/P_L calculation	simulation
TNT	1.630	6930	3.12				
Comp B	1.717	7980	2.98	80.00	80.93	1.19	1.17
RDX	1.836	8239	3.01	78.60	77.59	1.22	1.25
Octol	1.804	8330	3.07	77.82	76.44	1.24	1.28
PBX9404	1.842	8800	2.76	71.40	71.42	1.43	1.49

From the above results, it can be seen that the numerical simulation results are consistent with the expected results of theoretical calculation, which verifies the accuracy of the formula in this paper.

5 Conclusion

In the DLSC, the Mach wave propagates forward with convergent horn wave, the axis of the shaped charge can remain in the ODD state all the time. Study on the propagation law of detonation wave in DLSC with the wave shaper by numerical simulation. The results show that:

(1) In the DLSC, due to the difference in chemical and physical properties of the two explosives, when the HE shock initiation the LE, the detonation wave propagating in the LE near the contact surface will gradually deviating from the C–J condition. The paper obtained formulas for calculating the parameters of ODD state near the contact surface of the HE and LE.. And the functional relationship between the intensity of Mach wave and the incident angle of detonation wave in shaped charge is deduced. The accuracy of the formula was verified by the combination of theoretical analysis and numerical simulation

(2) Under all kinds of separating explosion conditions, the DLSC can form Mach wave at the axis of the charge. The separating explosion performance of the wave shaper determines the initial incident angle of the detonation wave at the axis and then determines the peak pressure of the Mach wave. Compared with the OSC, the peak value of Mach wave pressure in the DLSC is not increased, but the attenuation speed of Mach wave pressure can be delayed. The final parameters of ODD state in the DLSC are determined by the detonation velocity and the polytropic exponent of the explosive.

6 Symbols and Abbreviations

ODD	Overdriven detonation
OSC	Ordinary shaped charge
DLSC	Double-layer shaped charge
HE	High detonation velocity explosive
LE	Low detonation velocity explosive
$P(Gpa)$	Detonation pressure
$\rho(g/cm^3)$	Density
$u(m/s)$	Particle velocity
$D(m/s)$	Detonation velocity
$c(m/s)$	Sound velocity
k	Polytropic exponent
ξ	Overcompression coefficient
$\varphi(^\circ)$	Incident angle

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