Research Article

A Comparison Investigation on Cylinder Test in Different Ambient Media by Experiment and Numerical Simulation

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When the detonation reaction occurs after the charge in the warhead is ignited, the propagation of the detonation wave and the expansion of the detonation product will interact with the wrapped metallic shell and cause the shell material to accelerate, extremely deform, and eventually rupture, which is a typical strong fluid-structure interaction problem. In this paper, a comparison investigation on a cylinder test in different ambient media was implemented by experiment and numerical simulation, respectively. In the experimental test, the attention was paid to discussing the differences of the accelerating process of the cylinder metal wall, the expansion modes, and the fragment shape of the cylinder due to the medium with different shock wave impedance which surrounds the cylinder shell. For the numerical simulation, a coupling scheme of a meshless method and finite element method called the coupled finite element material point method was used to reproduce the cylinder expansion problem driven by explosive sliding detonation where the interaction between the cylinder wall and the explosive/detonation product is enforced by using a point-to-surface contact scheme to accurately achieve contact and separation between material particles and finite elements. Lastly, the macroscopic and microscopic states of the cylinder failure were compared and discussed for further discussion.

1. Introduction

The warhead is filled with high energetic materials and utilizes the detonation product, shock wave, and fragments to destroy the targets. The main factors affecting the damage efficiency consist of the density of the explosive, the detonation speed, the ability of acceleration, and the dynamical properties of the structure and material of the target. At present, the cylinder test is the simplest and the most feasible test method to evaluate the capability of an explosive and the dynamical properties of the cylinder material which was first proposed and applied by Kury et al. [1] of LLNL. In this test, the explosive is placed inside the metallic cylinder to be tested, and the charge is detonated at one end by a detonator or an explosive plane-wave lens. In the process of the detonation wave propagating to the other end of the cylinder, the high-speed scanning camera is used to record the cylinder wall expansion history. The image processing technology is used to obtain the expansion speed and the specific kinetic

energy and to characterize the characteristic quantity of the explosive capability. In the relevant fields including experimental design, testing, and data extraction of cylinder tests, a large number of research results can be referenced. Wang et al. [2] discussed the expansion, acceleration, and rupture process of cylindrical casing made of three types of material including TU1 copper, 50SiMnVB steel, and ANSI 1045 steel in the air medium by means of experimental tests and accurately measured the oscillation of velocity at the scanning slit of cylindrical casing by using the DPS (arrayed Doppler Photonic System). Goto et al. [3] studied the expansion and fracture process of cylinder and ring under the plane-strain and uniaxial-stress conditions by detonation load and gave the relevant coefficients of the Johnson-Cook damage model of cylindrical material based on the experimental data. Lindsay et al. [4] used the Shen-Castan edge detection algorithm to extract the expansion displacement curve of the cylinder wall from the slit expansion film more efficiently and accurately; meanwhile, a three-stage force formula model on the wall

expansion of the cylinder was proposed to capture the most prominent features of the expansion of the wall of the cylinder. In particular, it can commendably reproduce the peaks and valleys of the first reverberation of the velocity curve of the wall. In the existing researches, few papers have involved the expansion of the cylinder in the water medium. Yang et al. [5] investigated the detonation and postcombustion effects on the underwater explosion of an aluminized explosive which was not confined by any metallic shell with a meshless method, the MOC method. It focused on the nonisentropic flow due to postcombustion effect which affects the shock trajectory and gas-water interface. Hamashima et al. [6] obtained the JWL parameters of the detonation product of the cylindrical and spherical high explosives SEP which was not confined either by the shell through the nonideal detonation of the underwater explosion. Zhao et al. [7] researched the energy output characteristics of cyclotrimethylenetrinitramine- (RDX-) based aluminized explosives under the water with different aluminum content.

The cylinder test problem is a typical sliding detonation problem involving the propagation of detonation wave and the large deformation, fracture, and complicated phase changes of materials which are highly nonlinear. Meanwhile, the cylindrical metal, detonation product, and the outer cylinder medium form a complicated fluid-structure coupling system which increases the difficulty of numerical simulation. As one kind of meshfree particle method, the material point method [8] takes an advantage in the simulation of the dynamic response of materials under the initiation and the detonation of energetic materials. In particular, the solid material, the gas of the detonation product, and the detonation wave can be coupled under the uniform framework by the material point method which avoids the difficulty of the interface treatment. For example, Hu and Chen [9] studied the synergistic effects of concrete walls undergoing the action of the detonation of explosives and impact of fragments. Wang et al. [10, 11] used the material point method to evaluate the sliding detonation process of explosives and simulated the explosion welding between metal plates. Ma et al. [12] proposed an adaptive material point method to handle the numerical fracture problem in a one-dimensional shock tube; the method was also applied to solve the explosively driven metal flyer and the three-dimensional-shaped charge jet problem [13]. Yang et al. [14] introduced stochastic failure factors into the material model and successfully simulated the metal spherical shell rupturing process under the blast loading. Zhang et al. [15, 16] used the ignition growth equation to study the shock detonation process of solid explosives and further discussed the critical impact velocity of the flyer causing the explosion to detonate. Yang [17] studied the shock wave propagation problem and the dynamic response process of structure undergoing underwater explosion by using the generalized material point method. In order to avoid the numerical fracture problem of the material point method in simulating the propagation of detonation waves, Cui and Zhang [18, 19] established a coupling scheme of the material point method with the finite difference method for simulating the detonation wave propagation process and its coupling with the concrete target. Furthermore, the

material point method has achieved favorable applications in other fields such as hypervelocity impact [20, 21], incompressible fluid [22, 23], and molecular dynamics [24].

In this paper, the numerical method and experimental test will be used to investigate the cylinder expansion problem driven by sliding detonation of the explosive. Firstly, the cylinder expansion problem is introduced in Section 1. In Section 2, an improved version of the coupled finite element material point method and the contact algorithm is presented. In Section 3, the expansion process of the metal cylinder in the air medium is compared with that in the water medium by the test results and numerical methods. In Section 4, the rupture modes of the cylinder in the air/water medium are analyzed through the shock wave theory and microscanning technique. After the above research, it provides a reference for the explosion-driven problem of the underwater cylinder test.

2. Coupling of Finite Element Method with Material Point Method

The updated Lagrangian framework was applied in both the finite element method and the material point method; their weak form can be given as [8]

$$\int_V \delta u_i \rho \ddot{u}_i dV + \int_V \delta u_{i,j} \sigma_{ij} dV - \int_V \delta u_i \rho b_i dV - \int_{\Gamma_t} \delta u_i \bar{t}_i d\Gamma = 0, \quad (1)$$

where the subscripts i and j denote the components of the spatial coordinates following the Einstein summation convention, ρ is the density of the current state, b_i is the body force per unit mass, u_i is the displacement, δu_i is the corresponding virtual displacement, σ_{ij} is the Cauchy stress, Γ_t stands for the prescribed traction boundary of V , and $\bar{t}_i$ is the external traction.

2.1. Material Point Method. MPM is a hybrid method with Eulerian-Lagrangian description in which a material domain is represented by a collection of Lagrangian particles moving through a Eulerian background grid, as shown in Figure 1. The particles carry all state variables such as the mass, the position, the velocity, the acceleration, and the stress and strain, whereas the grid which carries no permanent information is used to solve the momentum equations and calculate the spatial derivative of physical variables. In this paper, the regular orthogonal grid is adopted for simplicity and high efficiency.

Since the whole domain is discretized by n_p particles, the spatial density can be approximated as follows:

$$\rho(x) = \sum_{p=1}^{n_p} m_p \delta(x - x_p), \quad (2)$$

where n_p is the sum of particles, m_p is the mass of particle p , δ is the Dirac delta function, and x_p is the location of particle p .

FIGURE 1: Material point method [8]: (a) material domain, (b) material represented by material points, and (c) discretization by material points.

When the momentum equations are solved in each time step, the background grid is attached rigidly to the particles and deforms with particles so that the grid can be viewed as a finite element discretization for the material domain. Consequently, the displacement $u_i(x)$ at any location can be approximated through

$$u_i(x) = \sum_{I=1}^{n_g} N_I(x) u_{iI}, \quad (3)$$

where n_g is the total number of grid nodes.

Substituting Equations (2) and (3) into the weak form Equation (1) and applying the lumped grid mass matrix yield

$$m_I \dot{v}_{iI} = f_{iI}, \quad I = 1, 2, \dots, n_g, \quad (4)$$

where $\dot{v}_{iI}$ is the velocity of grid node I ,

$$m_I = \sum_{p=1}^{n_p} N_{Ip} m_p \quad (5)$$

is the mass of grid node I and $N_{Ip} = N_I(x_p)$,

$$f_{iI} = f_{iI}^{\text{ext}} + f_{iI}^{\text{int}} \quad (6)$$

is grid nodal force, where

$$f_{iI}^{\text{int}} = - \sum_{p=1}^{n_p} N_{Ip,j} \sigma_{ijp} \frac{m_p}{\rho_p} \quad (7)$$

is the internal grid nodal force,

$$f_{iI}^{\text{ext}} = \sum_{p=1}^{n_p} m_p N_{Ip} b_{ip} \quad (8)$$

is the external grid nodal force and is the Cauchy stress and body force of particle p , respectively. The momentum Equation (4) in the background grid can be solved either by the

explicit integration scheme or by the implicit integration scheme (readers can refer to the related references [8] for more details). From the above discretization and computational process, it is found that the weak form is equivalent to the momentum equation and the traction boundary condition is the same in MPM and FEM. The biggest difference is that the particle quadrature is used in the material point method in each time step and Gauss quadrature in the finite element method.

2.2. Coupled Finite Element Material Point Method. In the impact problem with low and moderate striking velocity, the deformation of the metallic projectile is smaller than that of the concrete target. For handling this problem, Lian et al. [25] proposed a coupling scheme named the coupled finite element material point method (CFEMP) based on the updated Lagrangian framework. Then, an improved CFEMP scheme, a particle-to-surface contact algorithm rather than the grid-based contact method, was presented by Chen et al. [26]. It drew on the idea of the particle-to-surface contact algorithm in FEM to satisfy the contact conditions exactly at the contact interface, and it is convenient to implement the contact/slip/split between material particles and the finite elements. The improved contact version is comprised of four steps: In the first step, the information of the FEM grid is acquired to extract the surface mesh of the finite element grid. In the second step, establishing the potential contact pairs between the material points and the surface elements is carried out based on the possible contact event. In the third step, according to the potential contact pairs, the exact contact position and the gap for each contact pair are calculated by using a local search. In the last step, the contact force resisting the penetration into another body is imposed for each contact pair. The contact force applied on the material point is mapped into the background grid nodes, and that applied on the surface grid element is distributed to finite element nodes.

The existing numerical investigations show that improved CFEMP with the particle-to-surface contact algorithm was stable in the problems such as the free falling of a wedge into water and water column collapse with elastic baffle [26], and the efficiency and precision are better than the material point method and original CFEMP. However, further verification is needed in the gas detonation case with local extreme deformation.

3. Cylinder Expansion Test in Different Media

The main purpose of the cylinder test is to evaluate the capacity of acceleration for explosives. Generally, the typical cylinder test is carried out in an air medium under standard atmospheric pressure. Due to the very low shock wave impedance of air, the impedance of air medium on the acceleration of cylinder explosives is negligible in the theoretical analysis and numerical simulation. If the air medium is replaced by the water medium in the cylinder test, the influence of the water medium on the propagation of detonation wave as well as the cylinder expansion must be considered, because it is a typical fluid-structure interaction problem. In

FIGURE 2: The configuration of cylinder with charges.

FIGURE 3: The photo of the underwater cylinder test.

FIGURE 4: The whole experimental layout of explosively loaded metal cylinder test.

FIGURE 5: The wall-expanded negative in air medium.

this section, the cylinder tests in two different media were conducted and compared.

3.1. Cylinder Test Experiment and Its Layout. The cylindrical charges and configuration are shown in Figure 2. The main

FIGURE 6: The wall-expanded speed-time curve at the slit.

charge is made of TNT explosive, which was connected one by one in series with a size of $\phi 25 \text{ mm} \times 25 \text{ mm}$. The material of the cylinder is oxygen-free copper TU1 with an outer diameter of $d_0 = 30.12 \text{ mm}$, an inner diameter of $d_i = 25.0 \text{ mm}$, and a length of $L_0 = 300 \text{ mm}$. The detonation end was extended by one JH14 charge and ignited by a detonator, and the detonation velocity of the explosive was measured by an electric probe at each end of the copper cylinder. A SJZ-15 high-speed scanning camera was used for scanning slit during the test. In the process of test, the light source was provided by parallel backlight technology. The slit position was located at a position with a 200 mm distance from the detonation end, the camera speed was set to $6 \times 10^4 \text{ r/min}$, and its corresponding scanning speed was 3 km/s .

The experimental device of the underwater cylinder test is shown in Figure 3; the tank made of wood and plexiglas which has a length of 400 mm, a width of 300 mm, and a height of 300 mm was filled with water. The light source and scanning camera can be used because the front and rear observation windows are transparent. In our test, the argon-jet spark light source was adopted to supply the illumination. For safety reasons, relevant tests were carried out in the explosion tower of the Xi'an Modern Chemistry Research Institute. The whole experimental layout of the explosively loaded metal cylinder test is illustrated in Figure 4.

When the cylinder expansion test was happening, the expansion trajectory negative at the slit can be obtained through the scanning camera. As shown in Figure 5, the horizontal axis represents the time variable and the vertical axis

TABLE 1: The parameters for TNT explosive.

ρ_0 (g/cm ³)	A (Mbar)	B (Mbar)	JWL EOS		W	E_0 (kJ/cm ³)	C-J parameters	
			R_1	R_2			D (cm/ μ s)	P_{C-J} (Mbar)
1.589	3.712	0.0323	4.15	0.95	0.3	7.0	0.6874	0.21

TABLE 2: The material constants for TU1.

Material parameters			Johnson-Cook strength model							
ρ_0 (g/cm ³)	ν	E (Mbar)	A (MPa)	B (MPa)	n	c	m	$\dot{\epsilon}_0$ (s ⁻¹)	T_{room} (K)	T_{melt} (K)
8.96	0.35	1.29	90	292	0.31	0.025	1.09	1.0	293	1356

represents one-dimensional image of the slit expansion at the corresponding time. A microscope was used to manually interpret the scanning negative of the cylinder expansion. First, the starting position of the cylinder wall is determined by manual visual inspection as the origin of coordinates. Next, the ordinate and abscissa of the point at the interface are identified along the expansion trace at the equal axial distance, and then, according to the image magnification and the scanning speed, the expansion distance ($R - R_0$) of the cylinder wall and the corresponding expansion time t are calculated. Lastly, a series of $(R_j - R_0) - t_j$ data is obtained, and a curve can be fitted based on them. The above specific experimental data processing was described in the literature [1].

3.2. Cylinder Test and Numerical Result in Air Medium. The cylinder wall-expanded negative at the slit was obtained by a cylinder test in an air medium as shown in Figure 5. According to the data of $(R_j - R_0) - t_j$, the expansion speed-time curve of the outer wall of the cylinder can be obtained by the differential calculation as illustrated in Figure 6. The detail of data is supplemented in the supplemental file (available here).

In order to quantitatively investigate the propagation of detonation wave, the flow process of detonation products, and fluid-structure interaction between product gas as well as environmental medium and the cylinder shell, the improved CFEMP based on MPM3D (<http://comdyn.hy.tsinghua.edu.cn/english/mpm3d>) [27] software was used in this paper for numerical verification. Meanwhile, in order to compare the numerical accuracy with other numerical algorithms, the numerical results from the SPH/FEM, ALE/FEM, and Euler/FEM coupling schemes based on Autodyn software were listed in this subsection. In the numerical model, the detonation speed of the booster charge is close to that of the main charges inside the copper tube, so all charges were simulated based on the equation of state of the JWL (Jones-Wilkins-Lee) reaction product of TNT which takes the form of

$$p = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V}, \quad (9)$$

where $E = \rho_0 e$ is the internal energy per unit initial volume and ρ_0 is the reference density. ω , A , B , R_1 , and R_2 are

user-defined material constants. D is the C-J detonation velocity, P_{C-J} is the C-J pressure. All parameters are listed in Table 1. For the copper TU1, the Johnson-Cook strength model is adopted as follows:

$$\sigma_y = (A + B\bar{\epsilon}^n) \left(1 + C \ln \bar{\dot{\epsilon}}^* \right) (1 - T^{*m}), \quad (10)$$

where A , B , n , C , and m are material constants, $\bar{\epsilon}^* = \bar{\epsilon}/\dot{\epsilon}_0$ is the dimensionless effective plastic strain rate, $\dot{\epsilon}_0$ is the effective plastic strain rate corresponding to the quasistatic test used to determine the yield and hardening parameters A , B , and n , and $\bar{\dot{\epsilon}} = \sqrt{(2/3)\dot{\epsilon}_{ij}\dot{\epsilon}_{ij}}$ is the plastic strain rate. $T^* = (T - T_r)/(T_m - T_r) \in [0, 1]$ is the dimensionless temperature; T_r and T_m are the room temperature and melting temperature of the material. Its parameters are listed in Table 2 and the Mie-Grüneisen equation of state where $c_0 = 0.394$ cm/ μ s, $s = 1.49$, and $\gamma = 2.0$. In the CFEMP model, a quarter model was used in order to save the calculation cost and the effects of the air medium are ignored based on the previous analysis. The total length of cylinder charges is 325 mm which was discretized into 321099 particles with a space size of 0.5 mm, and the orthogonal cube grid is overlapped on the computational domain with a size of 1.0 mm $\times$ 1.0 mm $\times$ 1.0 mm. The copper tube with a length of 300 mm, an inner diameter of 25 mm, and an outer diameter of 30.12 mm was discretized by a finite element mesh which has 4848 nodes and 3000 elements. In SPH/FEM, ALE/FEM, and Euler/FEM coupling models, the two-dimensional axisymmetric model was used where the charges were discretized by SPH, ALE, or Euler, and all the copper tubes were discretized by the finite element method. Their sizes were consistent with those of the material particles and finite elements in CFEMP.

As shown in Figure 6, the numerical results of the expansion speed of the cylinder tube were compared with the experimental results at the slit ($L_1 = 200$ mm). It is found that the time when the cylinder wall at the slit simulated by several numerical methods started to expand was basically simultaneous at $t \approx 32.5 \mu$ s. In the beginning, the cylinder wall underwent a sharp radial expansion when the detonation wave front had passed the slit. When the explosive around the slit had completely reacted, the cylinder wall continued to expand under the action of the rarefaction wave and the reaction product. With the subsequent expansion

FIGURE 7: Comparisons of pressure contour by CFEMP and SPH/FEM schemes for cylinder test in air medium: (a) $t = 15 \mu s$, (b) $t = 30 \mu s$, and (c) $t = 45 \mu s$.

FIGURE 8: The configuration of the underwater cylinder test by CFEMP.

FIGURE 9: The wall-expanded negative in water medium.

of the detonation product, the expansion rate of the cylinder wall dropped significantly and tended to be a constant. Among these numerical methods, the numerical results of CFEMP are consistent with the results and trends of other numerical methods. However, two issues are found in the SPH/FEM scheme analogous to CFEMP. Firstly, the wave front region of the shock wave was widened to cause the copper wall to expand in advance, because the kernel function approximation was adopted in SPH and the influence domain of particle was enlarged. Secondly, the speed of cylinder wall expansion was significantly lower than the experimental value which is mainly due to the excessive numerical dissipation during the propagation process. On the other hand, the coupling scheme of the Euler method and the finite element method caused the contact force to decrease due to the penetration of the fluid-solid interface in the later stage. It led to the lower expansion speed of the cylinder wall than that of the experimental test. If the ALE/FEM scheme was used to discrete charge and cylinder tube, respectively, it can simulate large deformation and guarantee the nonpenetration at the fluid-solid interface, whose results are consistent with the experimental test as illustrated in Figure 6.

As illustrated in Figure 7, the pressure contours obtained by two numerical simulation methods including SPH/FEM and CFEMP were compared at three different times. The result of SPH/FEM was placed on the left side and the result of CFEMP on the right side. It is observed that the location of shock wave propagation and the deformation of the cylinder tube from two methods were symmetric basically. However, there were some anomalous particles with excessive pressure in the SPH/FEM scheme due to the tensile instability, which did not happen in the CFEMP scheme. On the other hand, the expanding velocity of particles in CFEMP was higher than that in SPH/FEM at the top of the cylinder tube, which is caused mainly by the interface instability of the material point method in the CFEMP scheme. In conclusion, the

two meshless methods coupled with the finite element method are suitable to simulate the sliding detonation of the explosive and the expansion and deformation process of the cylinder wall in the cylinder test; in terms of quantitative comparison, the result of CFEMP is closer to the experimental result compared with the SPH/FEM scheme.

3.3. Cylinder Test and Numerical Result in Water Medium.

Based on the standard cylinder test in the air medium, the air medium was replaced by the water medium as shown in Figure 3. The TU1 cylinder tube has an outer diameter of 30.12 mm, an inner diameter of 25 mm, and a length of 300 mm. In order to ensure the reliability of the installation of the detonator under the water, the length of the charge column is consistent with that of the cylinder tube, i.e., the detonation end and the left end of the cylinder tube are flush. In addition, other material parameters are consistent with the case in the air medium. The observation slit is also marked at the same position $L_1 = 200$ mm from the left end of the copper tube. The water tank is constructed by wooden and plexiglas plates, and the experimental device is suspended in the centre of the pool and fixed with iron wires as illustrated in Figure 3. In the numerical model of CFEMP, the TNT charges were discretized into 76224 material particles. The spacing length of each particle was set to 0.8 mm with a size of background grid of 1.6 mm $\times$ 1.6 mm. The TU1 tube was discretized by finite element mesh, and the finite element mesh in this case was consistent with that in the first case. The water domain was discretized into 4238869 material particles. The CFEMP model is shown in Figure 8. For the model of water, its viscosity was ignored in the strength model, and the Mie-Grüneisen polynomial was used in the equation of state. The formulation of EOS was given as follows:

$$p_H = \begin{cases} \rho_0 C_0^2 [\mu + (2s - 1)\mu^2 + (s - 1)(3s - 1)\mu^3], & \text{if } \mu \geq 0, \\ \rho_0 C_0^2 \mu, & \text{if } \mu < 0, \end{cases} \quad (11)$$

where $\mu = (\rho/\rho_0) - 1$ represents the compressibility of the material and c_0 and s are the relevant material parameters. These parameters related to water used in this paper are set as $\rho_0 = 1.0$ g/cm³, $c_0 = 0.165$ cm/ μ s, and $s = 1.92$. In SPH/FEM and ALE/FEM models, a two-dimensional axisymmetric model was established. The charge and water were discretized by SPH or ALE, and the cylinder tube was discretized by finite element mesh whose size and material model were consistent with those of finite element mesh applied in CFEMP.

As shown in Figure 9, the velocity-time curve of cylinder wall expansion at the slit was extracted from the cylinder test whose data is supplied in the supplemental file, and it was found that the expansion curve of the cylinder in the water medium was significantly different from that in the air. First, on the velocity peak of the curve, the value of the cylinder wall expansion (about 770 m/s) under the water was obviously smaller than that (about 1399 m/s) in the air medium. Second, for the trend of the velocity-time curve, the expansion speed curve of the cylinder in the air medium shows a

FIGURE 10: The pressure contour for cylinder test in water medium by CFEMP scheme: (a) $t = 10 \mu s$, (b) $t = 20 \mu s$, and (c) $t = 30 \mu s$.

monotonously increasing change. Oppositely, the curve of the cylinder in the water medium had a rapid increasing at the initial stage and then a slow decreasing. Compared with several numerical methods, the velocity-time curve simulated by the CFEMP method was basically the same as the experimental data at the beginning, the peak, and the latter stages. At the same time, by comparing the expansion negatives (Figures 5 and 9) of the cylinder tests and tests and the simulation configurations (Figures 7 and 10), it was found that the rate of the cylinder expansion under the water was smaller than that in the air medium. For the SPH/FEM method applied in this problem, due to the interface between the water and copper tube, the amplitude of the rarefaction wave which was reflected in the detonation product was greatly reduced, and then, the numerical energy dissipation in SPH/FEM was also reduced. According to the above analysis, the numerical results in the water medium by CFEMP and ALE/FEM schemes were closer to the experimental result than that in the air medium. The pressure contour by the CFEMP method is shown in Figure 10, from which the trajectory of the detonation wave front and the interface between the cylinder wall and the water can be clearly identified.

3.4. Investigation on the Propagation of Shock Wave in Different Media. The difference of shock wave impedance of the medium outside the cylinder wall leads to the distinguishing expanding pattern of the cylinder tube, which further changes the detonation energy and momentum transmission paths to cause the different distribution of detonation energy to the medium. In this subsection, the one-

dimensional shock wave theory was used to explain the issue. The cylinder tube coupling with air or water can be regarded as a multimedium system; the combination of different shock wave impedance media with a cylinder tube will cause the shock wave at the interface to reflect and transmit according to different manners. In the process of shock wave propagation in the cylinder test, it is supposed that the attenuation in the thin-walled cylinder is neglected, so the type of the stress wave reflected at the interface of two media just depends on the shock wave impedance of the media based on the shock wave theory. When the shock wave propagates from medium I to medium II, if the impedance of medium I is greater than that of medium II, the rarefaction wave will be reflected at the interface. On the contrary, the reflected wave is the shock wave if the impedance of medium I is less than that of medium II.

The Hugoniot curve of the undisturbed material can be obtained by using the mass conservation equation, the momentum conservation equation, and the shock compression law in the solid after the incident shock wave reached the interface as follows:

$$p = \rho_0 u(c_0 + su), \quad (12)$$

where ρ_0 is the initial density of the material, c_0 and s are related material parameters, and u is the particle velocity at the deformed domain. The parameters of the Hugoniot curve which refer to the EOS of material are listed in Table 3.

When the shock wave propagates to the interface of two media, the values of the reflected wave and the transmitted wave can be calculated by using the shock Hugoniot curve

TABLE 3: The parameters of Hugoniot curve.

	ρ_0 (g/cm ³)	c_0 (cm/ μ s)	s
TU1	8.96	0.394	1.49
Water	1.0	0.165	1.92

FIGURE 11: The analysis diagram of the stress wave propagation process.

or the isentropic p - u curve of the medium. As shown in Figure 11, the red and green solid curves represent the shock Hugoniot curve of different media (copper and water, respectively). The value of the slope from the original point to any point at the Hugoniot curve becomes large with increasing the shock wave impedance of the medium. The solid black curve indicates the isentropic curve of the TNT detonation product. According to the equation of state of the explosive, the parameters of the detonation wave at the C-J point, and the isentropic equation of the detonation product, the relationship between the lateral particle velocity and rarefaction wave pressure of detonation can be calculated as

$$u = \frac{2D\gamma}{\gamma^2 - 1} \left[1 - \left(\frac{p}{p_{C-J}} \right)^{(\gamma-1)/2\gamma} \right], \quad (13)$$

where u is the particle velocity and p is the pressure of incident shock wave at the interface, D is the explosive detonation wave speed and is set to be 0.6874 cm/ μ s, γ is the multi-index of the explosive and is set to be 2.727, and p_{C-J} is the C-J detonation pressure of explosive and is set to be 0.21 Mbar. As shown in Figure 11, the red dotted line is the isentropic curve of copper. For the sake of simplicity, the isentropic rarefaction wave curve is approximated by the

FIGURE 12: The wall-expanded velocity-time curve at the slit.

reflected Hugoniot curve; the specific form can be expressed as

$$p = \rho_0(2u_1 - u)[c_0 + s(2u_1 - u)]. \quad (14)$$

For the air medium, since its shock wave impedance is much lower than that of metal or water, it can be approximated as $p(u) = 0$. According to the illustration of Figure 11, when the detonation wave propagates along the copper tube, the intersection point ① between the Hugoniot curve of the copper and the isentropic curve of the detonation product represents the transmitted wave pressure and the particle velocity at the interface. When the shock wave in copper is transmitted into the water, since the shock wave impedance of copper is greater than that of water, the intersection point ② between the mirror symmetry of the Hugoniot curve of copper and the Hugoniot curve $p(u)$ of water represents the transmitted shock wave. Conversely, if the medium outside the copper is air, the intersection point ③ represents the transmitted shock wave at the interface below the intersection point ②. In the above two cylinder tests with different environmental media, the charge and copper materials were the same, so the time when the first shock wave peaks transmitted to the copper medium at the slit was consistent. As illustrated in Figure 11, the particle velocity at the interface when the shock wave is transmitted into the water medium is about 0.73 mm/ μ s (point ②) which is basically consistent with the initial expansion velocity peak of the outer wall of the cylinder in Figure 10, and the pressure of transmitted shock wave is about 2.0 GPa. In another case, when the shock wave is transmitted into the air medium, the particle velocity behind the shock wave front in the air is about 0.78 mm/ μ s (point ③), and the pressure of transmitted shock wave is neglected compared with the pressure in the water medium.

4. Discussion on Microscopic Analysis of Cylinder Damage

Based on the shock wave theory, the propagation process of shock wave in the medium was analyzed theoretically in the

FIGURE 13: The schematic diagram on the resultant force applied on the cylinder wall at the second stage: (a) in air medium and (b) in water medium.

FIGURE 14: Recycled fragments in the experiment.

previous section, but it could not quantitatively evaluate the work done by the detonation product acting on the copper tube. Through further numerical simulations and experimental measurements, it is found that the cylinder which is surrounded by different environmental media has different loading history curves as shown in Figures 6 and 12. In the air medium, the cylinder wall undergoes a typical process including sharp loading ($33 \mu s \leq t \leq 34 \mu s$), slow loading ($34 \mu s < t \leq 55 \mu s$), and shell fracture ($t > 55 \mu s$). But in the water medium, another process was presented which includes a sharp loading ($33 \mu s \leq t \leq 34 \mu s$), slow unloading ($34 \mu s \leq t \leq 80 \mu s$), and shell fracture finally. The essential reason is ascribed to the change of the resultant force applied at the cylinder wall. For example, the first stage of sharp loading was completed quickly under the first transmitted shock wave from the detonation product. At the second stage, on account of the superposition of transmitted shock wave at the detonation product/cylinder wall interface and the reflected rarefaction wave at the cylinder wall/air or cylinder wall/water interface, the cylinder wall was pressed by outside and inside forces collectively. In the case of the air medium, P_r was far greater than P_{air} at the first stage; the cylinder wall was accelerated rapidly. At the second stage, P_{air} raised due to the transmitted shock wave, but it was far less than P_r as illustrated in Figure 13(a). In the case of the water medium, P_r was also far greater than P_{water} at the first stage. After the transmitted shock wave reached the interface between the

cylinder wall and the water for the first time, P_{water} exceeded P_r gradually at the second stage as illustrated in Figure 13(b). Finally, for both cylinder tests, the cylinder wall kept expanding along the radial direction due to the gas expansion and the inertia. When the deformation of the cylinder wall approached the limitation of fracture, the copper wall will undergo a circumferential and axial fracture up to breaking up. As shown in Figure 14, we recovered some of the copper tube fragments from two tests. For the cylinder test in the air medium, most of the fragments are slender with an average length of about 26 mm and average width of 10 mm. Conversely, the fragments have a flake shape with an average length of about 270 mm and an average width of 14.7 mm for the cylinder test in the water medium.

In order to further study the microscopic failure mechanism of the cylinder tube driven by explosive, a scanning electron microscope (SEM, JSM580) was used to observe the microscopic scale of the metal fragments recovered after the test. For the first case in the air medium, the surface of the recovered fragments presents successive waves along the axial direction and no obvious strip-shaped appearance as shown in Figure 15(a-1). After zooming it in, the obvious local bulges were visible which is called dimple due to the outer surface under tension as shown in Figure 15(a-2). When the medium around the cylinder is water, the surface of the recovered cylinder fragments generally showed a relatively regular parallel strip along its axial direction. As shown

FIGURE 15: SEM photos of fragments in different media: (a-1) in the air ($\times 200$), (a-2) in the air ($\times 2000$), (b-1) in the water ($\times 200$), and (b-2) in the water ($\times 2000$).

in Figures 15(b-1) and 15(b-2), it shows obvious axial cracks without significant dimples.

5. Conclusions

In this paper, the sliding detonation law of the charging cylinder in different media was studied by numerical simulation and experimental methods. Firstly, an improved fluid-structure coupling numerical method, coupled finite element material point method, was applied to simulate the expansion process of the cylinder under sliding detonation. Secondly, the numerical accuracy of several different numerical methods was compared, and the accuracy of the coupled finite element material point method was verified by the experimental data. Numerical simulations and experimental tests have demonstrated the effect of different media on the expansion of the cylinder. The cylinder in the air medium has undergone three stages of sharp loading, slow loading, and shell rupture. In the water medium, the cylinder experienced a sharp loading, slow unloading, and final shell rupture. The cylinders have different expansion laws in different medium environments, mainly due to the difference of shock wave impedance, which causes the internal and external pressures acting on the cylinder to change. Finally, the macroscopic and microscopic states of the cylinder failure were compared and discussed, which provides a preliminary

reference for the subsequent investigation of the failure of the material.

Data Availability

The image data used to support the findings of this study are included within the supplementary file. And the image data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The file “Experiment data.doc” consists of two tables: Table 1 is the data of experimental data of the cylinder test in the air which is consistent with that in Figure 6; Table 2 is the data of experimental data of the cylinder test in the water which is consistent with that in Figure 12. (*Supplementary Materials*)

References

- [1] J. Kury, H. Hornig, and E. Lee, “Metal acceleration by chemical explosive,” in *Fourth Symposium (International) on Detonation*, pp. 3–13, White Oak, Maryland, USA, 1965.
- [2] X. Y. Wang, S. S. Wang, and F. Ma, “Experimental study on the expansion of metal cylinders by detonation,” *International Journal of Impact Engineering*, vol. 114, pp. 147–152, 2018.
- [3] D. M. Goto, R. Becker, T. Orzechowski, H. Springer, A. Sunwoo, and C. Syn, “Investigation of the fracture and fragmentation of explosively driven rings and cylinders,” *International Journal of Impact Engineering*, vol. 35, no. 12, pp. 1547–1556, 2008.
- [4] C. M. Lindsay, G. Butler, C. Rumchik, B. Schulze, R. Gustafson, and W. R. Maines, “Increasing the utility of the copper cylinder expansion test,” *Propellants Explosives Pyrotechnics*, vol. 35, no. 5, pp. 433–439, 2010.
- [5] C. Yang, X. Li, H. Yan, X. Wang, and Y. Wang, “Numerical study of the postcombustion effects on the underwater explosion of an aluminized explosive by a novel nonisentropic model for the detonation products,” *Journal of Energetic Materials*, vol. 37, no. 2, pp. 174–187, 2019.
- [6] H. Hamashima, Y. Kato, and S. Itoh, “Determination of JWL parameters for non-ideal explosive,” in *AIP Conference Proceedings*, vol. 706, pp. 331–334, Portland, OR, 2004.
- [7] Q. Zhao, J. Nie, Q. Wang, Z. Zhou, and Q. Jiao, “Numerical and experimental study on cyclotrimethylenetrinitramine/aluminum explosives in underwater explosions,” *Advances in Mechanical Engineering*, vol. 8, no. 10, 2016.
- [8] X. Zhang, Z. Chen, and Y. Liu, *The Material Point Method: A Continuum-Based Particle Method for Extreme Loading Cases*, Academic Press, 2017.
- [9] W. Q. Hu and Z. Chen, “Model-based simulation of the synergistic effects of blast and fragmentation on a concrete wall using the MPM,” *International Journal of Impact Engineering*, vol. 32, no. 12, pp. 2066–2096, 2006.
- [10] Y. X. Wang, Z. Chen, and M. Sun, “Numerical simulation of slippage detonation by material point method-MPM,” *Mechanics in Engineering*, vol. 29, no. 3, pp. 20–25, 2007.
- [11] Y. X. Wang, H. G. Beom, M. Sun, and S. Lin, “Numerical simulation of explosive welding using the material point method,” *International Journal of Impact Engineering*, vol. 38, no. 1, pp. 51–60, 2011.
- [12] S. Ma, X. Zhang, Y. P. Lian, and X. Zhou, “Simulation of high explosive explosion using adaptive material point method,” *CMES-Computer Modeling in Engineering & Sciences*, vol. 39, no. 2, pp. 101–123, 2009.
- [13] S. Ma and X. Zhang, “Adaptive material point method for shaped charge jet formation,” *Chinese Journal of Solid Mechanics*, vol. 30, no. 5, pp. 504–508, 2009.
- [14] P. F. Yang, Y. Liu, X. Zhang, X. Zhou, and Y. L. Zhao, “Simulation of fragmentation with material point method based on Gurson model and random failure,” *CMES: Computer Modeling in Engineering & Sciences*, vol. 85, no. 3, pp. 207–236, 2012.
- [15] Z. Zhang, W. D. Chen, and W. M. Yang, “The material point method for shock-to-detonation transition of heterogeneous solid explosive,” *Explosion & Shock Waves*, vol. 31, no. 1, pp. 25–30, 2011.
- [16] Z. Zhang, *Study on Material Point Method for Shock Initiation of Solid Explosive*, Harbin Engineering University, Harbin, Heilongjiang, China, 2010.
- [17] W. M. Yang, *Research on material point method for underwater explosion and shock problems*, [Ph.D. thesis], Harbin Engineering University, Harbin, Heilongjiang, China, 2013.
- [18] X. X. Cui, X. Zhang, X. K. Sze, and X. Zhou, “An alternating finite difference material point method for numerical simulation of high explosive explosion problems,” *CMES: Computer Modeling in Engineering & Sciences*, vol. 92, no. 5, pp. 507–538, 2013.
- [19] X. X. Cui, X. Zhang, X. Zhou, Y. Liu, and F. Zhang, “A coupled finite difference material point method and its application in explosion simulation,” *CMES: Computer Modeling in Engineering & Sciences*, vol. 98, no. 6, pp. 565–599, 2014.
- [20] P. Liu, Y. Liu, X. Zhang, and Y. Guan, “Investigation on high-velocity impact of micron particles using material point method,” *International Journal of Impact Engineering*, vol. 75, pp. 241–254, 2015.
- [21] Y. Liu, H. K. Wang, and X. Zhang, “A multiscale framework for high-velocity impact process with combined material point method and molecular dynamics,” *International Journal of Mechanics and Materials in Design*, vol. 9, no. 2, pp. 127–139, 2013.
- [22] F. Zhang, X. Zhang, K. Y. Sze, Y. Lian, and Y. Liu, “Incompressible material point method for free surface flow,” *Journal of Computational Physics*, vol. 330, pp. 92–110, 2017.
- [23] F. Zhang, X. Zhang, and Y. Liu, “An augmented incompressible material point method for modeling liquid sloshing problems,” *International Journal of Mechanics and Materials in Design*, vol. 14, no. 1, pp. 141–155, 2018.
- [24] N. F. He, Y. Liu, and X. Zhang, “Seamless coupling of molecular dynamics and material point method via smoothed molecular dynamics,” *International Journal for Numerical Methods in Engineering*, vol. 112, no. 4, pp. 380–400, 2017.
- [25] Y. P. Lian, X. Zhang, and Y. Liu, “Coupling of finite element method with material point method by local multi-mesh contact method,” *Computer Methods in Applied Mechanics and Engineering*, vol. 200, no. 47–48, pp. 3482–3494, 2011.
- [26] Z. P. Chen, X. M. Qiu, X. Zhang, and Y. P. Lian, “Improved coupling of finite element method with material point method based on a particle-to-surface contact algorithm,” *Computer Methods in Applied Mechanics and Engineering*, vol. 293, no. 15, pp. 1–19, 2015.
- [27] Z. T. Ma, X. Zhang, and P. Huang, “An object-oriented MPM framework for simulation of large deformation and contact of numerous grains,” *CMES: Computer Modeling in Engineering & Sciences*, vol. 55, no. 1, pp. 61–87, 2010.