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A novel electronic method for determining the flying characteristics of detonation-driven metal and the explosive equation of state

Kebin Li [a,b]*, Xuelei Shi [a], Xiang Chen [c], Xiaojie Li [d]

[a] Key Laboratory of Impact and Safety Engineering, Ministry of Education of China, Ningbo University, Ningbo, Zhejiang, 315211, China
[b] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing, 100081, China
[c] State Key Laboratory of Precision Blasting, Jianghan University, Wuhan, Hubei, 430056, China
[d] State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian, Liaoning 116024, China

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Abstract

The flying process of detonation-driven metal plate and tube is an important issue to evaluate the explosive welding quality of hard-to-weld metal materials and the energy release characteristics of condensed explosive materials. We developed a novel pressure-activated continuous velocity probe with trapezoidal support, i.e. Trapezoidal Support Velocity Probe (TSVP), by which the flying attitude measuring devices for flyer plate and copper tube were designed respectively. The detonation velocity can be obtained based on the parallel part of the probe assembly, and the flying process of the plate and tube can be calculated by using the inclined part data. Based on several groups of explosive welding tests and modified cylinder tests, the flying attitude curves were determined, which verified the simplicity and reliability of the test method. Besides, the polytropic EOS of the low detonation velocity explosive was determined by comparing the experimental results with the theoretical curves calculated by Richter formula. The Jones-Wilkins-Lee (JWL) EOS of detonation products of the high explosive was investigated by comparing the experimental fitting curves of the radial expansion displacement and velocity of copper tube with the finite element simulation results, whose inversing reliability was verified by contrast with the underwater explosion results.

Keywords: Explosive welding; Cylinder test; Detonation-driven metal plate and tube; Flying attitude; TSVP; EOS

of detonation products

1. Introduction

It is of great significance to understand the law of motion of metal plate and tube driven by sliding detonation for guiding explosive welding and determining the EOS parameters of explosive. When a planar or axisymmetric charge is detonated on the surface of a metal component, the expanding detonation products will directly act on the metal to drive them make two-dimensional flying motion. The determination of flying attitude is certainly critical to the reasonable selection of explosive welding parameters and the acquisition of good welding quality. On the other hand, the selection of type and parameters of detonation products EOS is the bottleneck problem to limit the accuracy of numerical calculation. Especially for commercial explosives with typical non-ideal detonation characteristics, whose significant diameter effect and heterogeneity of density and particle size will result in a big difference between the detonation parameters retrieved from the literature and the actual data. Directly applying these parameters for numerical calculation will have a huge impact on the results. Therefore, it is particularly important to develop a simple and reliable test method to quickly determine the on-site flying attitude of driven metal components and the EOS of detonation products.

Optical methods, including high-speed photography (HSP) [1-3]and flash X-ray radiography (FXR) [4,5], are often used to measure the flying attitude of detonation driven metal components. HSP has the characteristics of high spatial and temporal resolution and fast response rate, which can objectively record the high-speed movement process of objects. Cylinder test based on HSP was firstly proposed by Kury et al. of Lawrence Livermore National Laboratory (LLNL) [6], which was mainly applied for energy characteristic analysis of detonation driven problem and determination of EOS parameters. It is also widely used to determine the expansion fracture behavior of metallic cylindrical shell. In explosive welding, Wilson and Brunton, as early as 1970, used HSP to record the collision process between flyer and target, and analyzed the wave forming mechanism and the formation of jet. Recently, Bataev and Tanaka et al. [7] conducted more in-depth and systematic research on the formation of vortex wave and jet by integrating HSP, metallographic analysis and Finite Element Method-Smooth Particle Hydrodynamic (FEM-SPH) coupling method. FXR is a shadow photography technology widely used in the fields of ballistics, plasma physics and explosive dynamics. Smith et al. [8] and Takizawa et al. [9] used this method to investigate the accelerating process of flyer plate in 1971 and 1975 respectively. Bir Bahadur Sherpa et al. [10] made a theoretical and experimental study on the dynamic bending angle under the newly developed explosive with low detonation velocity by using FXR. Trzciñski and Szymañczyk [11,12] performed underwater explosion and cylinder test for a new explosive, and analyzed its energy release characteristics.

Although the optical method is more objective and reliable, there are many difficulties for field tests of large quantities in practice due to the complex apparatuses, high test cost, equipment protection and lighting source. In addition, there is a significant human error when processing the data of the negative film, especially the accurate determination of the wave front. Electrometric method, which uses electric probes or bare resistance wires as sensors, is another common means for measuring detonation-driven metal. For instance, scholars from the Swedish Blasting Research Centre designed a cylinder test device based on contact electric pins [13], by which they analyzed the diameter effect and work ability of 11 commercial explosives with different compositions and charge diameters between 40 and 100 mm. However, the experimental data obtained by discrete pins were limited, and the analysis accuracy of expansion displacement and velocity was greatly affected. The slanting wire methods, which was first proposed by Prümmer [14] in 1974, can continuously record the flying process of the flyer plate. The double slanted wire technique uses an oscilloscope to monitor the duration of the rising and falling process of the bare resistance wire to calculate the collision velocity and collision angle. Smith and Linde [15] designed a single slanted wire method, which only contained the rising part of the double technique. The collision velocity and collision angle can also be obtained based on the voltage signals. Even if the slanting wire methods can easily determine the trajectory of the driven metal components, it is vulnerable to electromagnetic radiation, metal jet, air shock wave and other external interference since the use of suspended bare resistance wire. On the other hand, the suspended resistance wire will be affected by the bending wave disturbance, whose test results may be invalid at all.

In the present research, a novel pressure-activated continuous velocity probe with trapezoidal support was developed, which can not only conveniently and reliably record the flying attitude of metal components, but also can determine the detonation velocity of explosives. Based on the novel probe, the experimental devices for monitoring the flying attitude of flyer plate and metal cylinder were designed respectively, and the corresponding data processing method was given as well. The flying trajectory of the plate and cylinder in several testing groups were successfully measured, from which the polytropic EOS of the low detonation velocity explosive was determined based on Richter theory of flyer plate motion, and the JWL EOS of detonation products of the high explosive was investigated based on the modified cylinder test data and the finite element simulation results.

2. Design of TVP

When applying the traditional slanting wire technique to measure the attitude of flyer plate, problems arise with the bending waves and electromagnetic interference, which have a serious impact on the test results. To solve these problems, a novel pressure-activated continuous writing velocity probe, i.e. Trapezoidal Support Velocity Probe (TSVP), as shown in Figure 1, was developed. The specific structure can be described as follows: a trapezoidal plexiglass sheet, 6 mm thick and 45° bevel, was selected as the support, whose length and height were determined by the test object. The upper platform surface and the inclined surface were coated with a shielding layer, and a single-layer of metal wire mesh fixed with an enameled resistance wire was adhered on it, all of which were covered with copper foil as the outermost shielding layer. Figure 1 shows the schematic structure and physical picture of TSVP, in which the metal mesh is stainless steel with a wire diameter of 0.12 mm and a hole diameter of 0.25 mm.

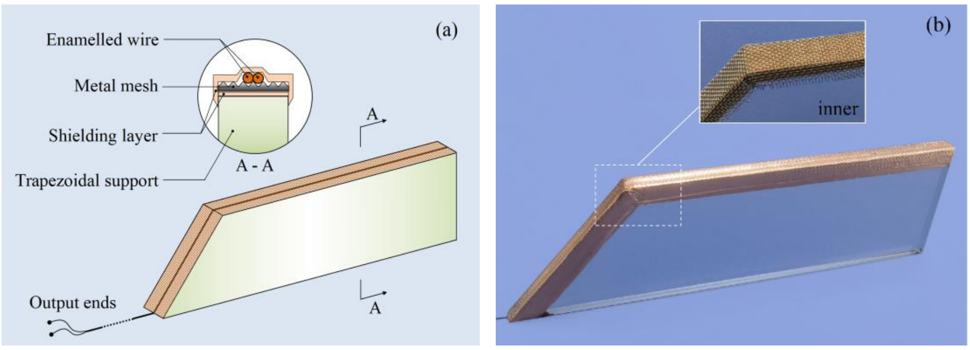


Fig. 1. Schematic illustration of TSVP (a) sketch map, (b) material object.

The conduction mechanism of TSVP is basically similar to the flexible threaded metal wire probe designed before[16-18], which uses the the threaded metal wire to impale the insulating layer of the enameled wire under high pressure. When it is fixed to the lower surface of the flyer plate or the outer surface of metal tube, the flying metal elements, due to the sliding detonation wave, collide with the upper parallel and inclined surface successively. By dealing with the voltage signal of the resistance wire, the movement speed of collision point (equals to detonation velocity) and the expansion parameters such as bending angle, radial expansion displacement and velocity can be calculated. The trapezoidal support prevents the probe from being hung in the air, which eliminates the effects of bending waves as a result.

To preliminarily analyze the conduction pressure and response time of TSVP, a LS-DYNA finite element model of the interaction between screw teeth and enameled wire was established as shown in Figure 2. Given a certain radius of the screw teeth curvature, we can determine the conduction pressure by changing the external pressure P_m and makingthe teeth just impale the insulating layer and contact the resistance wire. After a series of simulations for different radii of curvature, the relationship between impaling pressure and curvature radius was obtained as shown in Figure 2. It can be seen that the change of the curvature radius has a significant effect on the conduction pressure, which is below 8 MPa when the radius is too small (<0.01 mm), and higher than 600 MPa if it is too large (>0.4 mm). High sensitivity makes the probe is easy to conduct accidentally before a formal experiment, while low sensitivity may record an incomplete data. To meet the test requirements, the wire diameter of TSVP in this paper is selected as 0.12 mm (i.e. curvature radius is 0.06 mm), whose conduction pressure is 76 MPa judging from Figure 2. In addition, considering that the colliding pressure of the metal elements is generally above 10 GPa, it can be determined that the response time of the probe under the sliding detonation is less than 0.076 μs based on the numerical results.

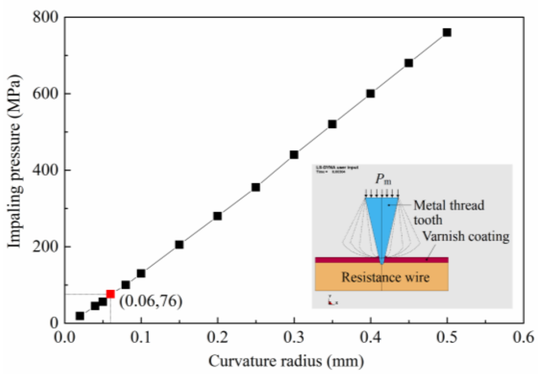


Fig. 2. Dependence of the impaling pressure on the curvature radius of the thread tooth probe

3. Experiments

The present section describes the experimental setup of explosive welding test and modified cylinder test based on TSVP. Four repeated experiments were performed respectively, and their voltage signals were successfully registered by an oscilloscope.

3.1 Experimental setup

3.1.1 Explosive welding test

The experimental installations for determining flyer plate attitude using TSVP is shown in Figure 3. The target plate and the flyer plate, with a gap of 20 mm, were both made of stainless steel, which were 800 mm in length, 200 mm in width and 2 mm in thickness. Ammonium nitrate/fuel oil (ANFO) was applied with a thickness of 20 mm, and the trapezoidal support was 100 mm long (upper side) and 20 mm high. The double-strand resistance wire, covered with copper foil as a shielding layer, was laid along the upper side and the hypotenuse of the trapezoid support and the upper surface of the target plate. Finally, The output end was led out from the rear of the plate and connected with the continuous detonation velocity recorder. When the explosive is detonated, a sliding detonation wave with high velocity will be formed above the flyer plate. Under the high-pressure impulse load, the flyer plate begins to bend downward and collide with the resistance wire on the horizontal side of the support. Since the horizontal movement speed of the bending point is equal to the velocity of the sliding detonation wave, the data recorded at this time is the detonation velocity of ANFO. Besides, Due to the subsequent detonation products, the flyer plate will continue to bend and accelerate to a velocity of hundreds of meters per second. When the detonation front reaches the upper corner, the bending flyer plate will make the resistance wire of the inclined side continue to conduct, and the data recorded now is the partial velocity of the flyer plate along the inclined side. Finally, the flyer plate will collide with the target plate when it reaches the bottom of the hypotenuse, and the speed of the collision point is equal to the detonation velocity as well. That is to say, the probe on the surface of the target also records the detonation velocity of the explosive. The present method not only avoids the influence of bending waves, but also makes it possible to continuous register the detonation velocity and the flying attitude in a single test.

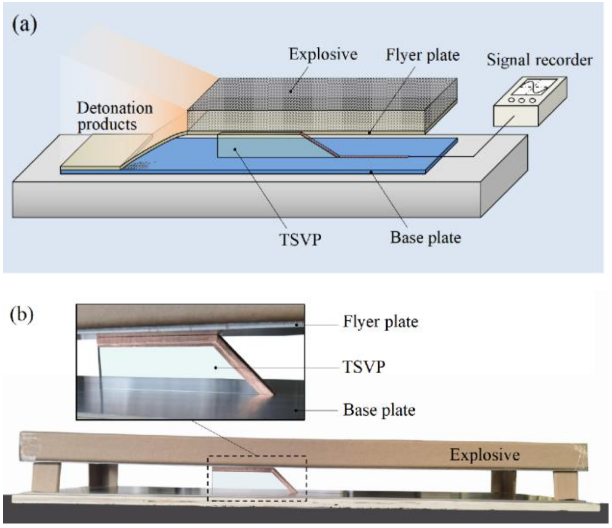


Fig. 3. Schematic representation of testing apparatus for flyer plate attitude using trapezoidal velocity probe: (a) sketch map. (b) site layout.

3.1.2 Modified cylinder test

The assembly of the modified cylinder test with TSVP is shown in Figure 4. The copper tube, filled with a certain density of powder RDX, is made of red copper and designed in accordance with standard size, 300 mm in length, 30.4 mm in diameter and 2.5 mm in thickness. In order to completely record the expansion radius, the trapezoidal sheet is 40 mm in height, and the distance between the starting end of TSVP and the detonating end is not less than 50 mm. Similar to the flyer plate bending process, a sliding detonation wave will be formed inside the copper tube after detonated as well. The tube wall will expand outward and collide with the resistance wire, and the parallel probe will obtain the detonation velocity, while the inclined section will register the expansion trajectory of the tube. If the recorder has multiple channels, multi probe assemblies can be arranged around the tube to ensure the effective recording and comparison of experimental data.

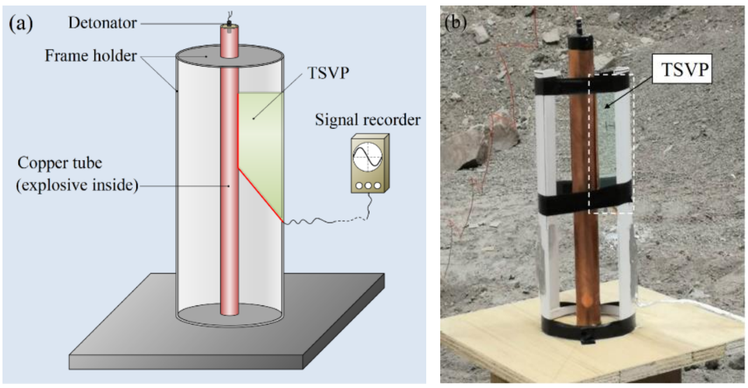


Fig. 4. Assembly configuration of improved trapezoidal velocity probe and copper tube: (a) sketch map. (b) site layout.

3.2 Experimental results

Four repeated experiments were carried out using the device shown in Figure 3. Both the target plate and the flyer plate were made of Q235 cold-rolled steel plates. The explosive density of No.FP-W-1~3 is 0.80 g·cm^{-3}, while the No.FP-W-4 is 0.82 g·cm^{-3}. The typical voltage signal is shown in Figure 5 (a), in which segment AB is the data of the parallel, segment BC is the inclined part, and CD is the target plate surface. It can be seen that the performance of TVSP is satisfactory since the resistance wire is reliably conducted throughout the whole process and the curve is smooth without oscillation. Four tests were also performed using the device in Figure 4, whose typical voltage signal obtained is shown in Figure 5 (b). Similarly, segment AB is the data of the parallel while BC is the inclined. It should be noted that the oscillation of initial segment may be caused by the electric detonator and the expansion of the detonation product. To reduce the influence on detonation velocity fitting, the length of the copper tube can be increased appropriately and the probe should be kept as far away from the open end as possible.

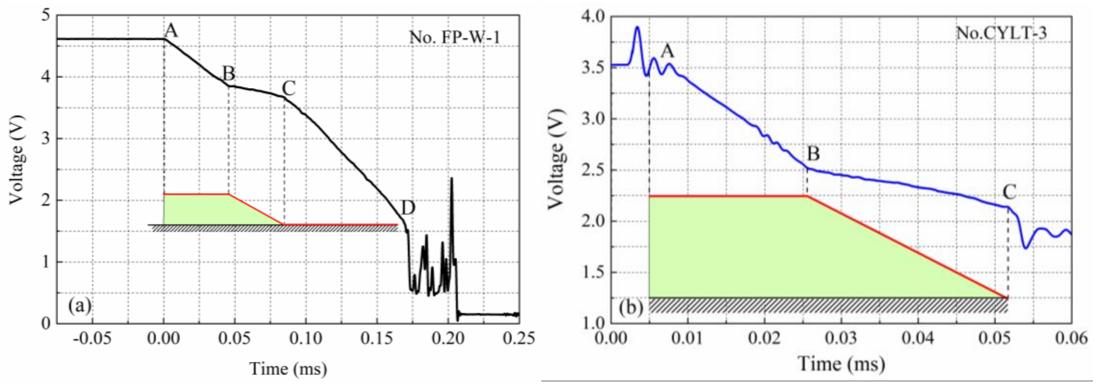
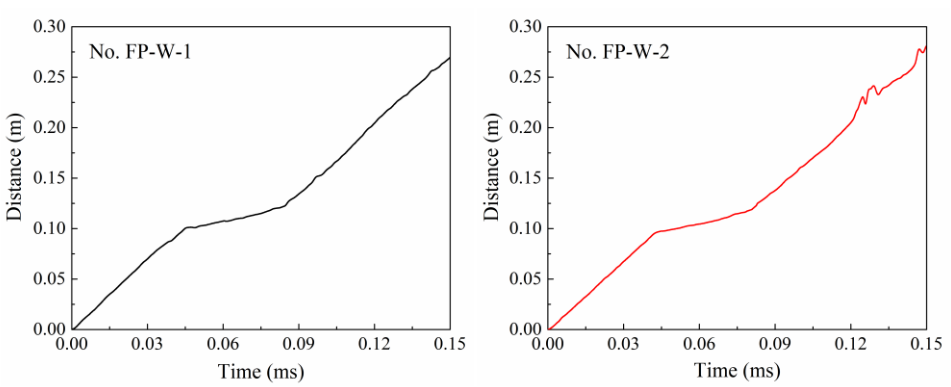


Fig. 5. A typical voltage signal curve of TSVP

4. Manipulation and analysis of experimental data

4.1 The total travelling data of the velocity probe

According to the test circuit of TSVP [18], the time history curves of conducting process in the explosion welding test, after converting the voltage signal, can be obtained as shown in Figure 6, which are smooth overall except for the light oscillation in the detonation velocity section of No.FP-W-4 test. Using linear fitting method for the data of the detonation velocity section, the detonation velocities of ANFO are then determined as shown in Table 1 (the plexiglass section is denoted as D_{e1}, and the target plate section is denoted as D_{e2}). It can be seen that the error of D_{e1} and D_{e2} for each test is 0.492%, 1.233%, 0.538% and 0.625% respectively, indicating that the two methods for obtaining the detonation velocity are reliable, and the detonation process is basically stable.



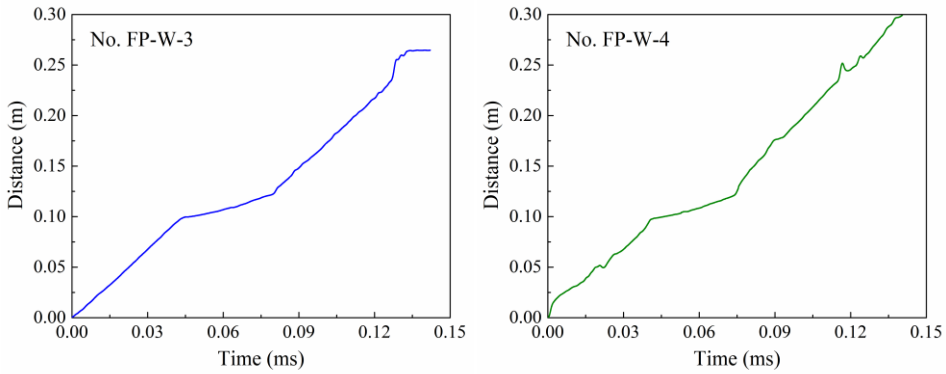


Fig. 6. Time history curves of conducting process in determination of flying attitude

Tab. 1. Detonation velocities fitted from the time history curves

Test No.	Detonation velocity (km·s^{-1})		Error
	D_{e1}	D_{e2}	
No.FP-W-1	2.2766	2.2941	0.492%
No.FP-W-2	2.2654	2.2658	1.233%
No.FP-W-3	2.3129	2.3254	0.538%
No.FP-W-4	2.5291	2.5450	0.625%

Similarly, the time history curves of conducting process in the modified cylinder test are shown in Figure 7. We can also linearly fit the parallel data to obtain the detonation velocity, while the detonation pressure can be calculated by the Kamlet formula [19], that is, for the $C_aH_bN_cO_d$ type explosive, the empirical expressions of detonation pressure p_{CJ} and the detonation velocity D_e are

$$p_{CJ} = 1.558\varphi\rho_e^2 \tag{1}$$

$$D_e = 1.01\varphi^{1/2}(1+1.30\rho_e) \tag{2}$$

where $\varphi = NM^{1/2}Q^{1/2}$ is a coefficient not sensitive to the composition of detonation products. p_{CJ} is the detonation pressure, GPa. D_e is the detonation velocity, km·s^{-1}. ρ_e is the charge density, g·cm^{-3}. N is the molar fraction of detonation products of unit mass of explosives, M is the average molecular weight of gas components in detonation products and Q is the chemical reaction heat of explosives, cal·g^{-1}. For RDX, its molecular formula is $C_3H_6N_6O_6$, whose N, M and Q are 0.0338, 27.2 and 1482 cal·g^{-1}, respectively, then φ=6.786. Since the RDX density in the experiment is known, the theoretical detonation pressure and detonation velocity in each test can be calculated based on formulas (1) and (2), and the polytropic exponent γ then be determined by using the relational formula $p_{CJ} = \rho_e D_e^2/(\gamma+1)$.

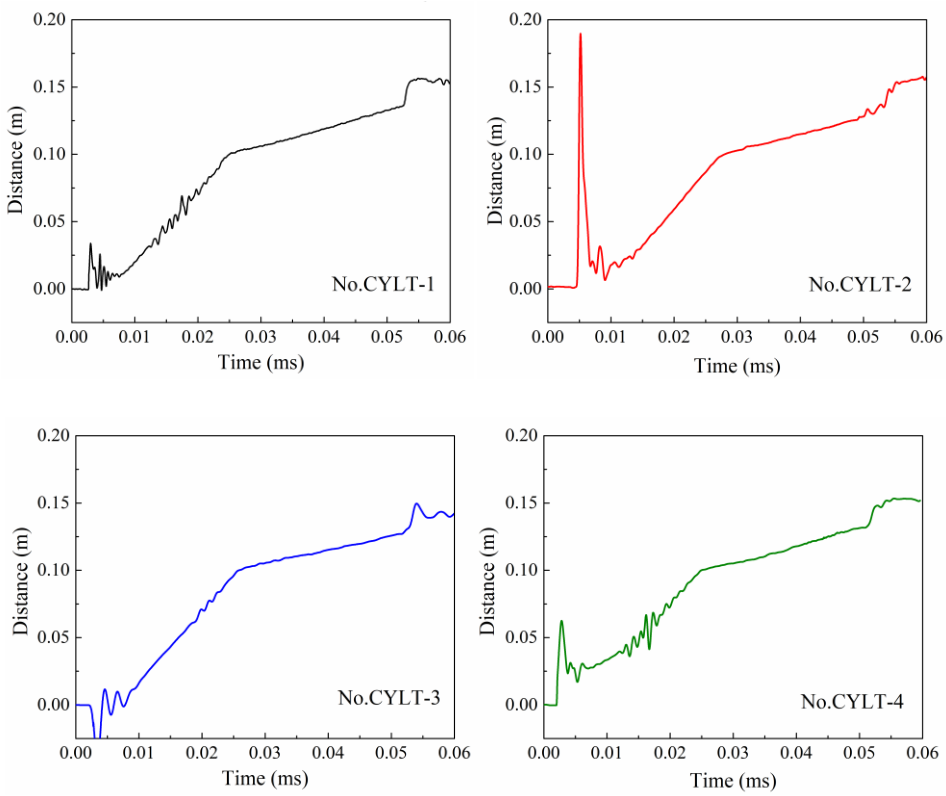


Fig. 7. Time history curves of trapezidal velocity probe obtained from four modified cylinder tests

The specific values of the detonation parameters in each test are shown in Table 2. The errors of the measured detonation velocity and the empirical values are 0.24%, 0.16%, 1.24% and 1.53%, respectively.

Tab. 2. Detonation parameters of RDX in cylinder test

Test No.	ρ_e /(g·cm^{-3})	D_e /(km·s^{-1}) Experimental	Calculated	Calculated p_{CJ} /GPa	γ
No.CYLT-1	0.82	5.4224	5.4357	7.075	2.408
No.CYLT-2	0.84	5.5129	5.5041	7.460	2.422
No.CYLT-3	0.79	5.2670	5.3331	6.598	2.322
No.CYLT-4	0.82	5.3525	5.4357	7.109	2.305

4.2 Trajectory curves of the plate and tube

The hypotenuse of TSVP and the flying element in Figure 3 and Figure 4 are enlarged as shown in Figure 8 to illustrate the geometric relationship between the inclined probe and the flyer plate or the copper tube. The initial element OB arranged in parallel at time t_0 bends into curved surface BE after t_m-t_0, whose maximum bending angle is $\theta_{w,max}$. The flying attitude of the element at any middle time is AN, and the bending angle is θ_w. If the detonation front reaches a certain point B on the element, assuming that the detonation wave has stabilized at this time, the flying process will be a steady motion. That is to say, if a horizontal line is drawn through the N point (x_N, y_N) to intersect the M point (x_M, y_M) on the BE, the shapes of AN and BM are the same, and the velocity of the element in the horizontal direction is V_d, which equals to D_e. Therefore, it can be found that the geometric relationship between the inclined probe of trapezoidal support and the flying element can be expressed as

$$\begin{cases} x_{\mathrm{m}} = x_{\mathrm{n}} + V_{\mathrm{d}}\left(t_{\mathrm{m}} - t_{\mathrm{n}}\right) \\ y_{\mathrm{m}} = y_{\mathrm{n}} \end{cases} \tag{3}$$

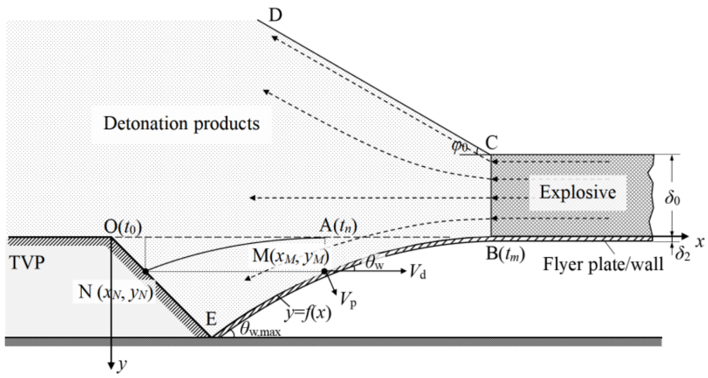


Fig. 8. Geometric relation diagram of declining velocity probe and flying plate

Using the formula (3), the flying attitude of the plate in each explosive welding test can be obtained as shown in Fig. 9, where the forward direction of detonation wave and vertical upward are the positive directions of X-axis and Y-axis respectively. At the moment, the detonation front has reached the position of x=80 mm. It also can be seen that the longest travel distance in the vertical direction is about 16 mm, while the actual spacing between the target plate and the flyer plate is 20 mm. It means that the data of the last $4\sqrt{2}$ mm of the hypotenuse is also included in the CD segment of Figure 5. We speculate that the thin slope end of the trapezoidal support may have broken before the probe is conducted, as a result, it approximately becomes a horizontal segment to record the moving speed of the colliding point. Nevertheless, according to experience for ANFO, the flyer plate tends to move at a uniform speed when the flying distance is greater than 0.8 times the thickness of the explosive. In addition, the bending angle reaches the maximum value at same time. That means the curves measured in this paper meet the length requirements, but we suggest that the support height can be appropriately increased to get more stable section data in the follow-up study.

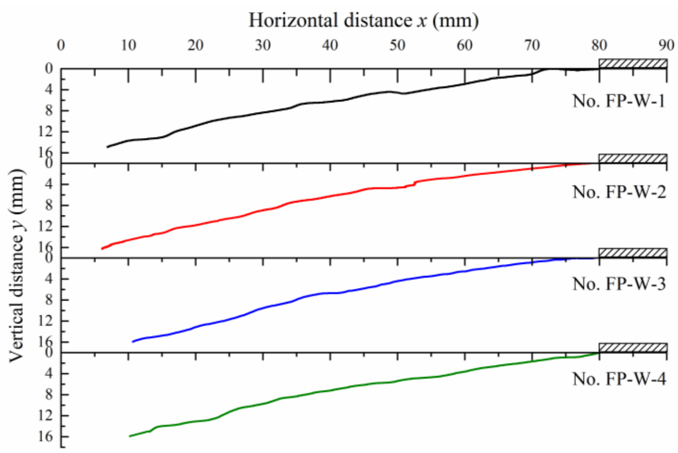


Fig. 9. Experimental curves of flying plate attitude under sliding detonation wave

Similar to the data processing of the flyer plate attitude, the expansion law of the copper tube, combined with the geometric correspondence of formula (3), can be determined from the data in the second half of the experimental curve in Figure 7. The radial expansion displacement is shown in Figure 10, where the detonation front has reached a position 140 mm away from the detonating end. By analyzing the rupture position of the copper tube (i.e. the farthest point where the probe is conducted), it can be determined that the maximum radial expansion distances of the copper tube are 23.14, 19.81, 22.75, and 23.41 mm, respectively, and the maximum expansion angles (i.e. the maximum angle between the expansion outline and the initial wall) are 11.28°, 11.37°, 11.05°, and 11.14°, respectively.

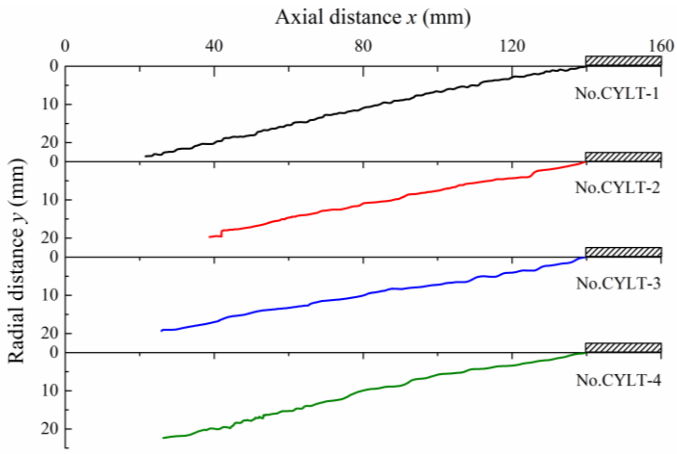


Fig.10. Radial expansion of copper tube in modified cylinder test

5. Parametric determination of explosive EOS

5.1 Determination of the γ-law EOS of ANFO explosive based on the flyer plate attitude

The polytropic exponent γ of explosive is an important parameter to describe the movement of flyer plate, whose value varies with the type and density of the explosive, and changes with the decay of the pressure of the detonation product, especially for the low detonation velocity explosives used in explosive welding. Traditionally, the γ-law EOS is often determined by aquarium test, which calculates the γ based on the determination of detonation pressure by the impedance matching between the explosive and the water. However, aquarium test usually use cylindrical charge, while explosive welding mainly take the form of plane charge, resulting in the flawed description for the characteristics of the detonation products. After obtaining the flying attitude of the plate, we can finally determine the specific value of γ for plane ANFO by comparing the different γ corresponding to the Richter approximate analytical solution[20].

According to Richter's theory of flyer plate motion, the $y(x)$ curve describing the spatial attitude of the plate can be determined by the following two equations

$$\frac{y}{\delta_0} = (1+\gamma)\frac{\theta_{\mathrm{w,max}}}{\bar{R}}\int_0^{\theta_{\mathrm{w}}}\frac{\sin\theta_{\mathrm{w}}}{\left(\theta_{\mathrm{w,max}}-\theta_{\mathrm{w}}\right)}\mathrm{d}\theta_{\mathrm{w}} \tag{4}$$

$$\frac{x}{\delta_0} = (1+\gamma)\frac{\theta_{\mathrm{w,max}}}{\bar{R}}\int_0^{\theta_{\mathrm{w}}}\frac{\cos\theta_{\mathrm{w}}}{\left(\theta_{\mathrm{w,max}}-\theta_{\mathrm{w}}\right)}\mathrm{d}\theta_{\mathrm{w}} \tag{5}$$

where θ_w is the dynamic bending angle, whose maximum value is $\theta_{w,max}$. δ_0 is the thickness of the explosive, and $\overline{R}$ is the mass ratio of the explosive and the flyer plate.

$\theta_{w,max}$ satisfies the following relationship

$$\frac{1}{\theta_{w,max}} = \frac{1}{\varphi_0} + \frac{c_w}{\overline{R}} \tag{6}$$

where φ_0 is the inclination of the detonation product expanding to the air, which depends on the characteristics of the explosive as well as the constant c_w. They can be expressed by γ as

$$\varphi_0 = \frac{4\sqrt{\left(1-\frac{1}{\gamma}\sqrt{\gamma^2-1}\right)}}{\sqrt{3}} \tag{7}$$

$$c_w = \frac{\sqrt{3\left(\gamma^2-1\right)}}{2\gamma\sqrt{1-\frac{1}{\gamma}\sqrt{\gamma^2-1}}} \tag{8}$$

If the density, thickness and detonation velocity of the explosive are determined, the flying attitude then depends on γ, which means different γ will correspond to a specific flying curve. Therefore, according to the research method of inverse problem, the value of γ can be deduced by comparing the experimental flying attitude with the theoretical curves. Taking No.FP-W-1 as an example, a smooth flying curve can be obtained by fitting the flying trajectory with cubic terms. After that, δ_0 and $\overline{R}$ can be determined based on the known experimental conditions. If the polytropic exponent of ANFO is assumed to be γ, then φ_0, c_w and $\theta_{w,max}$ are determined according to equations (6)~(8), and the Richter approximate solution can be calculated by programming. Since the polytropic exponent of low detonation velocity explosives is between 1.6 and 2.4, we take 0.1 as the value step, and draw the experimental curve and the theoretical curves in a same figure (as shown in Figure 11). By comparing the coincidence degree between the experimental and the theoretical curves, the γ-law EOS of ANFO can be established easily.

In Figure 11, the abscissa is the horizontal distance, and the ordinate represents the flying displacement of the plate in the vertical direction. It can be seen that the bending angle is inversely proportional to the γ value. The blue curve with the graphic symbol is the flying attitude fitted from the experimental results, which is basically consistent with the curve of γ=2.0. Then we can infer that the polytropic exponent of the detonation products in the No.FP-W-1 test is 2.0. Similarly, the polytropic exponents of No.FP-W-2~4 can be determined as 2.0, 2.0, and 2.1, respectively.

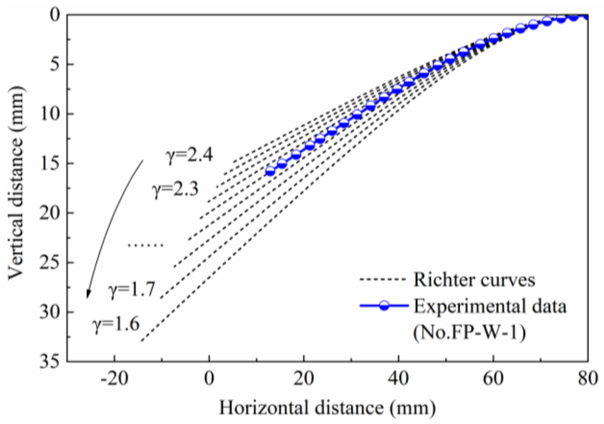


Fig. 11. Determination of explosive adiabatic exponent by flying plate attitude curves

5.2 Determination of JWL EOS of RDX explosive based on modified cylinder test

In order to invert the EOS parameters of the detonation product based on the cylinder test data, it is necessary to further process the expansion trajectory of Figure 10. The Hornberg and volk's method [21] is applied to fit the relationship between the expansion displacement of the cylinder mass center plane and time into the following form

$$\Delta r_{\mathrm{m}} = r_{\mathrm{m}} - r_{\mathrm{m},0} = a\left\{\left(t+t_0\right) - \frac{1}{b}\left[1-\mathrm{e}^{-b\left(t+t_0\right)}\right]\right\} \tag{9}$$

where $r_{\mathrm{m},0}$ is the initial radius of the mass center plane of the cylinder, mm; r_{m} is the changing radius in the expansion process, mm; t is the expansion time of the outer wall, μs. A correction parameters of time term is introduced, and $t+t_0$ represents the expansion time of the cylinder mass center plane, resulting in $\Delta r_{\mathrm{m}}=0$ when $t+t_0=0$. a, b and t_0 are obtained by fitting the experimental data.

Taking the time derivative of Eq. (9), the radial expansion velocity of the mass center plane can be obtained

$$u_{\mathrm{m}} = \frac{\mathrm{d}\Delta r_{\mathrm{m}}}{\mathrm{d}t} = a\left[1-\mathrm{e}^{-b\left(t+t_0\right)}\right] \tag{10}$$

According to the above analysis, the outer radius of the copper tube in Fig. 10 is first transformed into the change law of the center radius, which is then nonlinearly fitted using the formula (9). Finally we can obtain the fitting curves of radial expansion displacement of the four tests as shown in Fig. 12(a), whose fitting coefficient is shown in Table 4. The expansion velocity curves determined by formula (10) is shown in Fig. 12(b).

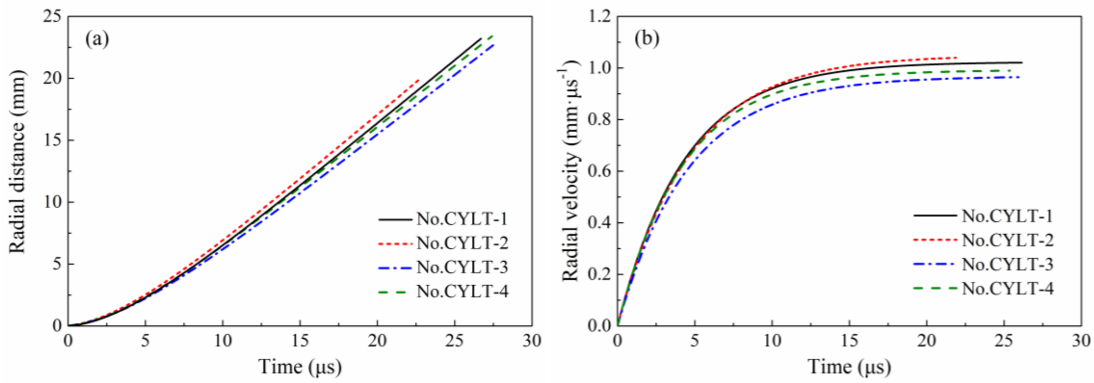


Fig. 12. Fitting curves of radial expansion displacement and velocity of cylinder tests

Tab. 4. Fitting coefficients of expansion curves of copper tube

Test No.	a/(mm·μs^{-1})	b/μs^{-1}	t_0/μs	Fitting degree
No.CYLT-1	1.0234	0.2294	2.6598	0.9994
No.CYLT-2	1.0494	0.2344	2.2658	0.9927
No.CYLT-3	0.9679	0.2178	3.1554	0.9916
No.CYLT-4	0.9923	0.2351	3.1159	0.9971

On the basis of the inversion method of the JWL EOS, a two-dimensional fluid-structure coupling model of copper tube expansion driven by detonation wave is firstly established by using AUTODYN program (as shown in Figure 13). The tube applies Lagrangian grid, and the material is CU-OFHC (high-conductivity oxygen-free copper, Johnson-Cook model), whose specific parameters use the default values of the AUTODYN material library. While the explosives use Euler grid, whose ends are linearly detonated, and the detonation parameters are shown in Table 2. The air also uses Euler grid, and the state equation and corresponding parameters use the default values of the material library. The center position of the upper tube wall is selected as the gauge point, and the JWL coefficients in the program are continuously adjusted until the error between the radial expansion displacement of the gauge point and the experimental result is less than ±0.5%, and the expansion velocity is less than ±1%. Taking No.CYLT-1 as an example, the comparison between the simulation curve and the experimental results for the expansion displacement and velocity is shown in Fig. 14.

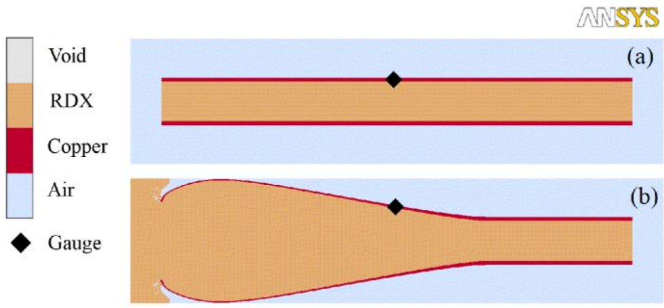


Fig.13. Two-dimensional fluid-structure coupling model of copper expansion under the explosive detonation driving

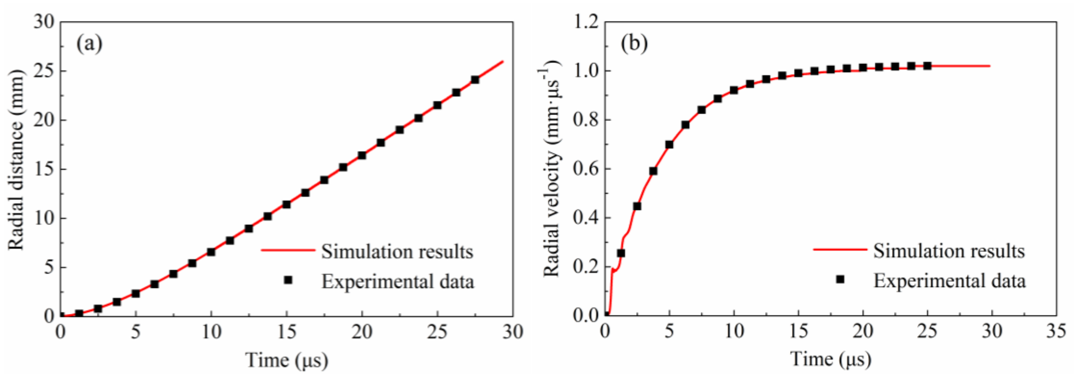


Fig. 14. Comparison of radial expansion displacement (a) and velocity (b) for cylinder test (No.CYLT-1)

Finally, the coefficients of the JWL EOS of the RDX detonation products determined by the cylinder test are shown in Table 5. The corresponding *p-V* expansion isentropes are shown in Fig. 15, in which the isentropic curves determined by underwater explosion test are also given [22]. Due to the different charge density in the two types of tests, the detonation velocity and detonation pressure are inconsistent. Besides, the inverse methods are dissimilar. There is a difference between the *p-V* curves, but both remain within a reasonable range, which can be used as a reference for each other.

Tab. 5. The coefficients of JWL EOS of RDX determined from cylinder test

Test No.	*A* /GPa	*B* /GPa	*C* /GPa	R_1	R_2	ω
No.CYLT-1	210.59	9.22	0.395	6.00	1.40	0.28
No.CYLT-2	214.51	8.69	0.376	5.85	1.35	0.28
No.CYLT-3	196.03	10.71	0.409	6.30	1.58	0.29
No.CYLT-4	207.20	10.30	0.353	6.20	1.43	0.29

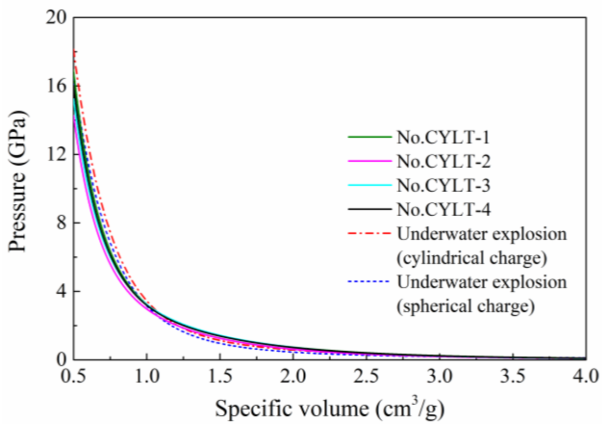


Fig.15. *p-V* expansion isentropes of RDX determined from cylinder test

6. Conclusions

In order to obtain a convenient and economical new way to determine the key parameters of explosive welding, as well as the equation of state of detonation products, this paper developed a Trapezoidal Support Velocity Probe, a pressure-activated velocity probe that can be conducted under high-speed collision of metal components, which makes it possible to continuously record the detonation velocity of explosive and flying attitude of metal component. Test devices for the flying attitude of explosive welding and cylinder test were designed using TSVP. Four field tests were performed respectively and the total travelling data of the velocity probe were recorded correspondingly. On the basis of analyzing the geometric relationship of declining velocity probe and flying plate, the travelling data were converted into flying attitude curves, which can be used to analyze the quality of explosive welding and determine the EOS parameters.

The relationship between the attitude of the flyer plate and the polytropic exponent γ was established for low explosives used in explosive welding. By comparing the flying attitude curves measured in experiments with the theoretical curves obtained from approximate analytical solutions, we deduced that the γ of the detonation products of the ANFO was approximately equal to 2, which means that the polytropic equation of state was determined. As to RDX explosive, the radial expansion displacement and expansion velocity of the copper tube were obtained based on the Hornberg & Volk's formula. By building a two-dimensional fluid-structure coupling model for the expansion of the detonation-driven copper tube, the simulation results of the radial expansion displacement and expansion velocity of the copper tube were compared with the experimental curves with errors of less than ± 0.5% and ± 1%, respectively. Finally, the JWL EOS of RDX detonation products was determined.

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