Propellants, Explosives, Pyrotechnics

DOI: 10.1002/prep.201800226

Use of a Reverberation Technique to Determine Grüneisen Parameter of Unreacted Plastic bonded Explosive

Shuang Qin,[a, b] Xu Zhang,*[b] Jun Ming Liu,[b] Zheng Yu,[b] Feng Zhao,[b] Rong Zhang,[b] and Bin Zhong[b]

Abstract: Grüneisen parameter plays an important role in describing states of materials, especially for highly condition-depended detonation process. Herein, this key empirical parameter of unreacted plastic bonded explosive (PBX) is determined by a multiple shock-reverberated technique. The explosive sample is sandwiched between copper plates, within which, shock waves reverberate and compress explosive continuously. This rapid dynamic process is verified by the stepped pressures measured by embedded PVDF stress gauges. The Mie-Grüneisen equation of state is utilized to calculate the off Hugoniot reverberated states, which have a better agreement with experiments compared to the impedance match method. Five shots of such explosive produce enough experimental data to fit the most reliable Grüneisen parameter. This work demonstrates the accuracy of the shock-reverberated technique applied to insensitive explosive to determine Grüneisen parameter and provides reference for further study on unreacted JB-9014.

Keywords: Plastic bonded explosive · off Hugoniot state · Grüneisen parameter · Mie-Grüneisen equation of state

1 Introduction

The heterogenous plastic bonded explosive consists of 95-wt.% tri-amino-tri-nitro-benzene (TATB) powder and coated 5-wt.% adhesive [1]. The TATB based explosives are important, because they can meet the request of modern weapons with tremendous releasing energy and simultaneously high security for storage [2]. Since they are difficult to be initiated, it is necessary to determine their detonation sensitivity. The accurate detonation process requires an understanding into the nonreactive explosive, the complete detonation product, and a single reaction-rate law describing the conversion of these two [3]. Generally, the flow model for the initial detonation assumes a mixture of unreacted component and complete detonation product. In order to calculate the mixing ratio of these two-phases, the equation of state (EoS) for unreacted explosive must be given in advance [4].

Much attention has been given to the shock Hugoniot relation (or EoS) of unreacted insensitive explosives in the long-term study [5,6]. Earlier, the Hugoniot relations for unreacted explosives were often obtained by the inconvenient wedge experiment [7]. Recently, Zhang *et al.* [8] used a symmetric flyer impact experiment, with embedded manganin stress gauges and successfully measured the shock Hugoniot relation of PBX. Milne *et al.* [9] used plate impact experiments and achieved the unreacted Hugoniots of three PBX. But the Hugoniot relation requires atmosphere pressure and room temperature for its initial state, which sometimes limits its application.

The Mie-Grüneisen EoS as one of the most widely used EoS in modeling shock waves of explosives goes beyond this limitation. It describes the relation between pressure and volume of solid at any given temperature [10]. The Grüneisen parameter Γ as a key parameter in the Mie-Grüneisen EoS, can be derived functionally from thermodynamic or in an *ab initio* way from lattice dynamics [11]. However, the theoretical expression of Grüneisen parameter is difficult to determine, because the microscopic structure of explosive during detonation process has huge uncertainty and complexity. The conventional method to determine this parameter is to combine the Mie-Grüneisen EoS with the high-pressure experimental results, using the Hugoniot (mostly available from Los Alamos Shock Hugoniot Data [12]) or isentrope curve as a reference to modify the Mie-Grüneisen EoS [13].

Since the Mie-Grüneisen EoS is incomplete, thermodynamic parameters should be determined from experimental measurements or from different theoretical models with approximations. The plate impact technique is often used to measure the EoS of unreacted explosives. However, it will induce big changes of volume and temperature after the post-shock, which could bring serious problems, such as re-

[a] *S. Qin*
CAS Key Laboratory of Mechanical Behavior and Design of Materials (LMBD) Department of Modern Mechanics,
University of Science and Technology of China,
Hefei, 230026, China
[b] *S. Qin, X. Zhang, J. M. Liu, Z. Yu, F. Zhao, R. Zhang, B. Zhong*
National Laboratory of Shock Wave and Detonation Physics
Institute of Fluid Physics
China Academy of Engineering Physics
Mianyang, Sichuan, 621900, China
**e-mail: caepzx@sohu.com*

action or melting of explosive. The multiple shock reverberation technique can avoid the above problems, because explosives in this approach can be compressed step by step. When a shock wave encounters a boundary between two media with different shock impedances, it will transmit and be reflected. The reflected shock wave further compresses the explosive and the next reflected shock wave will do the same until the system achieve an ideal stable high-pressure state. This multiple reverberated shock dynamic behavior was observed by Kondo *et al.* in fused quartz with embedded gauges [14].

In this work, this multiple shock-compression technique is applied to study the EoS of the unreacted PBX. The reverberated compressed states are described by both the approximated impedance match solution and the accurate Mie-Grüneisen EoS. The influence of the Grüneisen parameter on the expression is given. The parameter with the minimum error comparing to the experiments will be determined as the empirical value of the explosive. The polyvinylidene fluoride (PVDF) piezoelectric gauges are used in the experiment to measure the in-situ pressure profiles. Compared to other embedded pressure gauges (magnetic particle velocity gauge [15], manganin pressure gauge [16]), the PVDF piezoelectric gauge has mechanical flexibility, high shock charge output, micrometer-scale thickness and similar shock impedance with explosive sample [17].

This paper is organized into five sections. Theories and calculation details are briefly introduced in Sec. 2 for both the impedance match solution and the Mie-Grüneisen EoS. Sec. 3 gives information of the experimental configuration and the recording system. The results of the experiments and calculations are presented and discussed in Sec. 4. Finally, the conclusion is summarized in Sec. 5.

2 Theoretical Section

Each multiple reverberated shock state is calculated by the formulas based on conservation of mass, momentum and energy, as shown in Eq. (1) to Eq. (3):

$$\rho_{i-1}(U_s - u_{i-1}) = \rho_i(U_s - u_i), \tag{1}$$

$$p_i - p_{i-1} = \rho_{i-1}(U_s - u_{i-1})(u_i - u_{i-1}), \tag{2}$$

$$p_i u_i - p_{i-1}u_{i-1} = \rho_{i-1}(U_s - u_{i-1})\left[\left(E_i + \frac{u_i^2}{2}\right) - \left(E_{i-1} + \frac{u_{i-1}^2}{2}\right)\right]. \tag{3}$$

p, U_s, u, ρ and E denote pressure, shock-wave velocity, particle velocity, density, and internal energy, respectively. The sub-(i−1) or sub-i refers to conditions ahead of or behind the shock wave. The particle velocity, shock wave velocity, and internal energy at each reverberated state are given by

$$u_i - u_{i-1} = \pm\sqrt{(p_i - p_{i-1})(v_{i-1} - v_i)}, \tag{4}$$

$$U_s - u_{i-1} = \pm v_{i-1}\sqrt{\frac{p_i - p_{i-1}}{v_{i-1} - v_i}}, \tag{5}$$

$$E_i - E_{i-1} = \frac{1}{2}(p_i + p_{i-1})(v_{i-1} - v_i), \tag{6}$$

where v is specific volume. The positive sign denotes that the shock wave propagates in the positive direction (from left to right in this work) and the negative sign denotes the opposite direction.

2.1 The Impedance Match Method

The analytical impedance match solution in the P-u space is a convenient method to describe the reverberated states of explosive. It combines the shock Hugoniot relations and the momentum conservation equation.

The initial state of PBX sample is $P_0^e = 0$ and $u_0^e = 0$, so the Eq. (2) can be simplified as

$$p_1^e = \rho_0^e U_s^e u_1^e = \rho_0^e\left(C_e + S_e u_1^e\right)u_1^e, \tag{7}$$

where U_s^e and u_1^e are the shock velocity and particle velocity of explosive, respectively. The superscript and subscript respectively show the different samples and various states. The initial density of PBX is $\rho_0^e = 1.895$ g/cm^3. p_1^e is the initial pressure measured by the PVDF gauge in our experiment. The principal Hugoniot locus of the unreacted PBX can be obtained from Reference [18] as $C_e = 2.4188$ km/s and $S_e = 2.1396$. The bulk sound speed C_e and the slope of the relation S_e are empirical parameters characterized by explosive. The fitting line covers the range from 0.4 to 1.2 mm/μs.

Based on the continuity conditions of pressure and particle velocity across the impactor and target interface, the pressure of impact point is given by

$$p_{im} = \rho_0^{Cu} U_s^{Cu} u_p^{Cu} = \rho_0^{Cu}\left(C_{cu} + S_{cu}\left(V_{\text{impact}} - u_1^e\right)\right)\left(V_{\text{impact}} - u_1^e\right), \tag{8}$$

the density of copper at ambient condition is $\rho_0^{Cu} = 8.929$ g/cm^3 and the principal Hugoniot data of copper is available as $C_{cu} = 3.933 \pm 0.0042$ km/s and $S_{cu} = 1.500 \pm 0.025$ [19]. V_{impact} is the impact velocity of the copper flyer. The impact point is the intersection of Eq. (7) and Eq. (8).

The reverberated states in the unreacted PBX sample can also be calculated from Eq. (2) and Eq. (8), Note that particle velocity should be substituted by $(u_i)_{cal}$. The calculated particle velocity $(u_i)_{cal}$ for i state in the multiple shock-reverberated experiment is given by

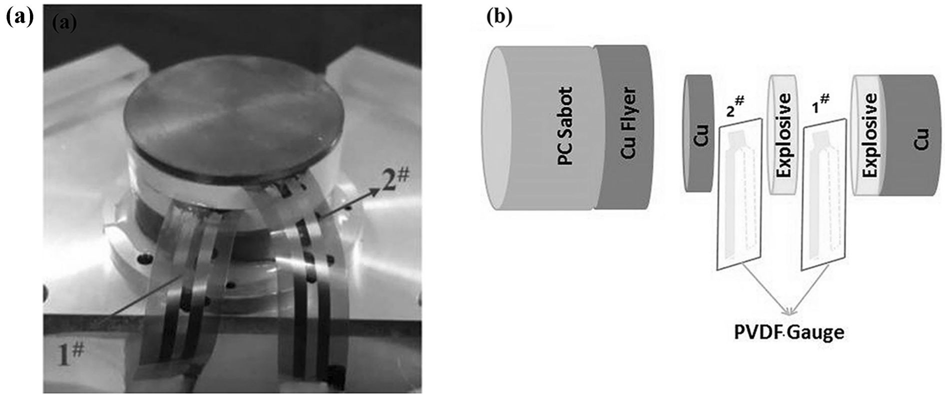

Figure 1. (a) Sample assembly of the shock reverberation experiment; (b) Schematic of the sample assembly.

$$(u_i)_{cal} = (u_{i-1})_{cal} + (-1)^{i-1}(u_i - u_{i-1}). \tag{9}$$

This calculation uses the original Hugoniot curve in *P-u* plane with graphic mirror method, in which Hugoniot curve is determined by the atmospheric pressure and room temperature. However, the reverberated state *i* here is related to the previous state $i-1$ which has been changed to a high pressure and high temperature. Therefore, this method is not so accurate to evaluate the reverberated states.

2.2 The Mie-Grüneisen Equation of State

The reverberated state in unreacted PBX explosive deviates from the normal Hugoniot state. It should be described by the Mie-Grüneisen's model, in which the EoS is given by

$$p = p_c + \frac{\Gamma}{v}(E - E_c), \tag{10}$$

p_c and E_c are the pressure and internal energy at zero temperature ($T = 0$ K). The Grüneisen parameter Γ represents the thermal pressure contribution from a set of vibrating atoms. Using the Hugoniot relation as a reference curve, the Eq. (10) is modified by

$$p = p_H + \frac{\Gamma}{v}(E - E_H). \tag{11}$$

The Hugoniot equations in *P-v* plane and *E-v* plane are expressed as

$$P_H(\nu_i) = \frac{C_e^2(\nu_0 - \nu_i)}{(\nu_0 - S_e(\nu_0 - \nu_i))^2}, \tag{12}$$

$$E_H(\nu_i) = \frac{1}{2}P_H(\nu_i)(\nu_0 - \nu_i), \tag{13}$$

where ν_0 is initial special volume.

From Eq. (6), (11), (12), and (13), the shocked *i* state pressure can be derived from $i-1$ state. The relation is given by

$$P_i = \frac{P_H(\nu_i) + \frac{\Gamma}{\nu_i}\left[\frac{P_{i-1}}{2}(\nu_{i-1} - \nu_i) + E_{i-1} - E_H(\nu_i)\right]}{1 - \frac{\Gamma}{2\nu_i}(\nu_{i-1} - \nu_i)}. \tag{14}$$

From the Eq. (14) the *i* state is determined by the $i-1$ state. The P_i values are measured by the PVDF gauge in our experiments. Each reverberated state can be evaluated combing Eq. (2), (4), (12), (13), and (14), if Γ has been guessed. Comparing theoretical results calculated from each estimated Γ with the experiments, the most reliable value of Γ with the minimum error will be finally determined.

3 Experimental Section

3.1 The Shock-Reverberation Experimental Configurations

In the multiple shock-compression experiments, the explosive sample is sandwiched between two copper plates with higher shock impedance. It will then be continuously compressed by multiple reverberations of the shock waves. The experimental sample assembly for pressure measurement is shown in Figure 1 (a) and the corresponding detailed schematic of target sample assembly is shown in Figure 1 (b). Table 1 gives the specific parameters of each

Table 1. Experimental parameters of sample assembly.

Target Assembly	Copper Flyer [mm]	Copper Delay [mm]	PBX Sample 1 [mm]	PBX Sample 2 [mm]	Copper Reflector [mm]
Dimensions	$\phi 50 \times 10$	$\phi 42 \times 2$	$\phi 42 \times 5$	$\phi 42 \times 5$	$\phi 42 \times 15$

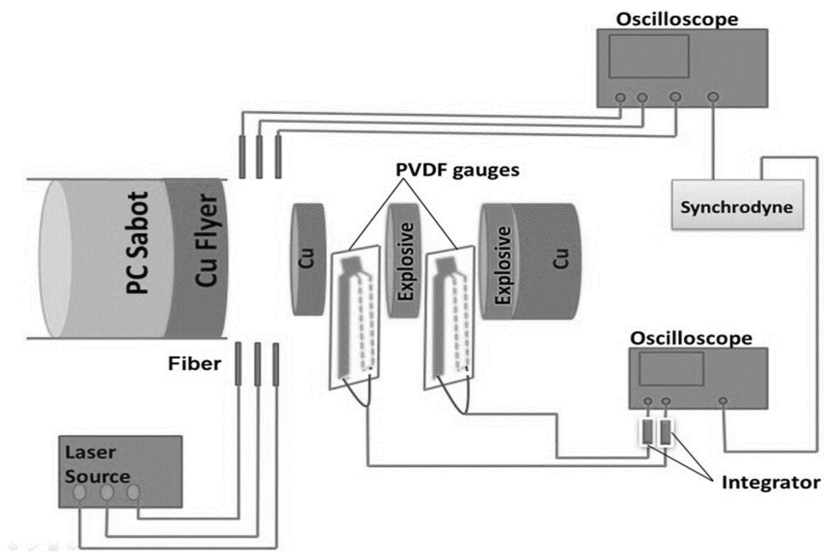

Figure 2. Schematic of measurement system configuration.

sample assembly. Each element of the target assembly is bonded by silicone rubber. The shock wave is first generated at the impact surface and then propagates through the whole explosive samples. When shock wave in the explosive with low shock impedance encounters the right-side copper with high impedance, it will be reflected at the boundary and yield a higher pressure. The shock waves after that are reflected between boundaries of PBX sample and copper for several times. The two PVDF gauges are mounted at the surface of the copper and the explosive to record this procedure. The total thickness of PVDF gauge is about 80 μm and the pressure versus time history is determined by the calibration curves.

The schematic of the measurement system is shown in Figure 2. The powder gun with a 57 mm caliber launches a projectile. It has a velocity from 0.513 to 1.074 mm μs^{-1} in different shots. The projectile impacts the target sample and yields a high input pressure. In the symmetric impact experiment (the flyer and the target are of the same material), an equilibrium particle velocity is half of the flyer's velocity. The velocity of the flyer in this experiment can be measured by the parallel laser light source technique. The experimental system is placed in the vacuum chamber, which is evacuated to 150 Pa (1.13 Torr) or less. Until now, this measurement setup has been successfully investigated the shock detonation or the reaction-build-up process for some PBXs [20].

3.2 The Recording Circuit of Gauge Charges

The PVDF piezoelectric gauge can be regarded as a charge source under the external dynamic force. Within pressure range concerned, the charge released by the gauge is proportional to the shock pressure. In most cases, current-mode and charge-mode measurements are both available to gather the gauge's electrical signal [20].

In the current-mode measurement, a resistor is connected in series with the gauge. As the current is recorded, the charge density is then obtained by numerical integration of the current. This recording technique measures the rate of stress change, and so requires fast recording instruments, because the shock pulse duration of the derivative need be the same as the rise time of the electrical signal [20]. While in the charge-mode measurement, the electrical charge is measured by a capacitor in series with the gauge. The capacitor gathers the charges directly released by the gauge and does not need the high recording precision for instrument. In our experiment, we choose the charge-mode to directly record the output charges. Figure 3 shows the equivalent circuit corresponding to the charge-mode measurement. The output recording system consists

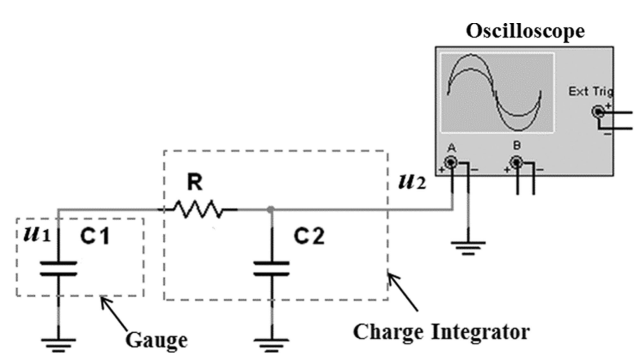

Figure 3. Equivalent circuit corresponding to the charge-mode recording.

of a charge integrator and an oscilloscope. $C_1 = 10$ pF is the capacitance of the gauge [21]. The capacitance of charge integrator is $C_2 = 0.1$ μF, and the resistance of $R = 50\ \Omega$ eliminates the mis-match situation from the coaxial cable. The capacitance of the low loss coaxial cable is $C_c = 100$ pF per meter which adds the magnitude of capacitance C_1 (the 2.5-meter long coaxial cable is used in the experiments). From the electric circuit analysis, the output charge of the integrator $Q_2(t)$ is calculated by

$$Q_2(t) = \frac{C_2 Q_0}{C_1 + C_2}\left(1 - e^{-\frac{t}{\tau}}\right), \tag{15}$$

where $\tau = RC_1C_2/(C_1+C_2) \approx 13$ ns is the circuit's time constant. $Q_0(t)$ is the initial charges related to the piezoelectricity of the PVDF gauge.

4 Results and Discussions

4.1 The Multiple Shock Reverberated Experiment

In multiple reverberated shock experiments, the target assembly system consists of a delay copper plate, the sample and a reflection copper plate. The two PVDF gauges provide the in-situ pressure measurements of the PBX. The left-side gauge 2# records the input pressure P_1 and the starting time point when the flyer impacts the explosive, as dashed lines shown in Figure 4. The measured pressure in gauge 2# maintain stable for about 1 μs but then gradually decline, which cannot reveal the characteristic of multiple reverberated shock waves. The reason is that the rarefaction waves generated from the rear of copper flyer prevent further compression, according to our estimation of shock duration by the length of flyer and the shock velocity of copper.

Therefore, we mount another gauge noted 1# at the midway of the explosive. As shown in Figure 4, the gauge 1# pressure profile shows a rapid rising pressure induced by reflected shockwaves. A stepped pressure process within the explosive is recorded. The reverberated shock states are noted as numbers. The first and damping first steps ($i = 1, 1'$) represent the arrival of the first shock wave. The time interval between starting points of the gauge 2# and the gauge 1# represents the propagation time for shock wave through the left part of the sample. The second and third steps ($i = 2, 3$) represent the reverberated shock states. These shock waves are generated at the interface between copper and explosive. But they will be slightly impeded when propagating in the explosive. According to the measured jump 1 and jump 1′ pressure values, the damping factor g of shock pressure within this sample can be simply estimated. The measured pressure values in each shot thus need to be modified by this damping factor g, which is approximately 0.19 per millimeter. There is a pressure attenuation at the end of each stage (more evident for higher stages) due to the presence of rarefaction wave, Taking Shot 2 in Figure 4 (b) as an example, the maximum equilibrium pressure is obtained after two shock reverberations and the stepped pressure lasts about 4 μs. A pressure decays after the third stage. The duration of time in stage 2 is shorter than stage 1′, due to the more compressed volume of sample and higher shock velocity.

The observed shock state parameters in each shot are shown in Table 2 except the values recorded by the Gauge 2# in Shot 1 and Shot 4 (beyond measurement error). The corresponding pressure profiles recorded by the in-situ PVDF gauges for each Shot are shown in Figure 4.

Table 2. Experimental measurements of each shock state.

Shot No.	Flyer Impact Velocity [mm μs^{-1}]	Gauge No.	Shock Jump No.	Measured values Time [μs]	Pressure [GPa]
1	0.513	2#	Shot 1–1	/	/
		1#	Shot 1–1′	157.559	2.4737
			Shot 1–2	160.075	4.7496
			Shot 1–3	162.142	6.0369
2	0.634	2#	Shot 2–1	137.076	3.2900
		1#	Shot 2–1′	138.543	3.1196
			Shot 2–2	140.908	6.2902
			Shot 2–3	142.852	7.7229
3	1.074	2#	Shot 3–1	78.968	6.8812
		1#	Shot 3–1′	80.176	6.3014
			Shot 3–2	82.015	14.2077
4	0.825	2#	Shot 4–1	105.523	/
		1#	Shot 4–1′	106.847	4.3017
			Shot 4–2	108.947	8.6754
5	1.003	2#	Shot 5–1	91.390	5.3036
		1#	Shot 5–1′	92.637	5.0698
			Shot 5–2	94.611	10.6730

4.2 Graphical Impedance Match Solution

The impedance matching solution is used to calculate the multiple reverberated shock states. The calculating process is detailed in Sec. 2.1.

Comparison of the calculated pressure and time of each state with the experimental values is summarized in Table 3, in which the observed delta time means the interval time between two nearest jumps. Table 3 gives the deviation between the calculated and measured values, the formula of which is given by

$$d = \sqrt{\left(\frac{\Delta P}{P_{calc}}\right)^2 + \left(\frac{\Delta t}{t_{calc}}\right)^2}. \tag{16}$$

The impact initial state $i = 1$ is calculated by the intersection between the Hugoniot relations of copper flyer and explosive sample in P-u plane. The average deviation of the initial point in each shot is about 10.04%. The reverberated

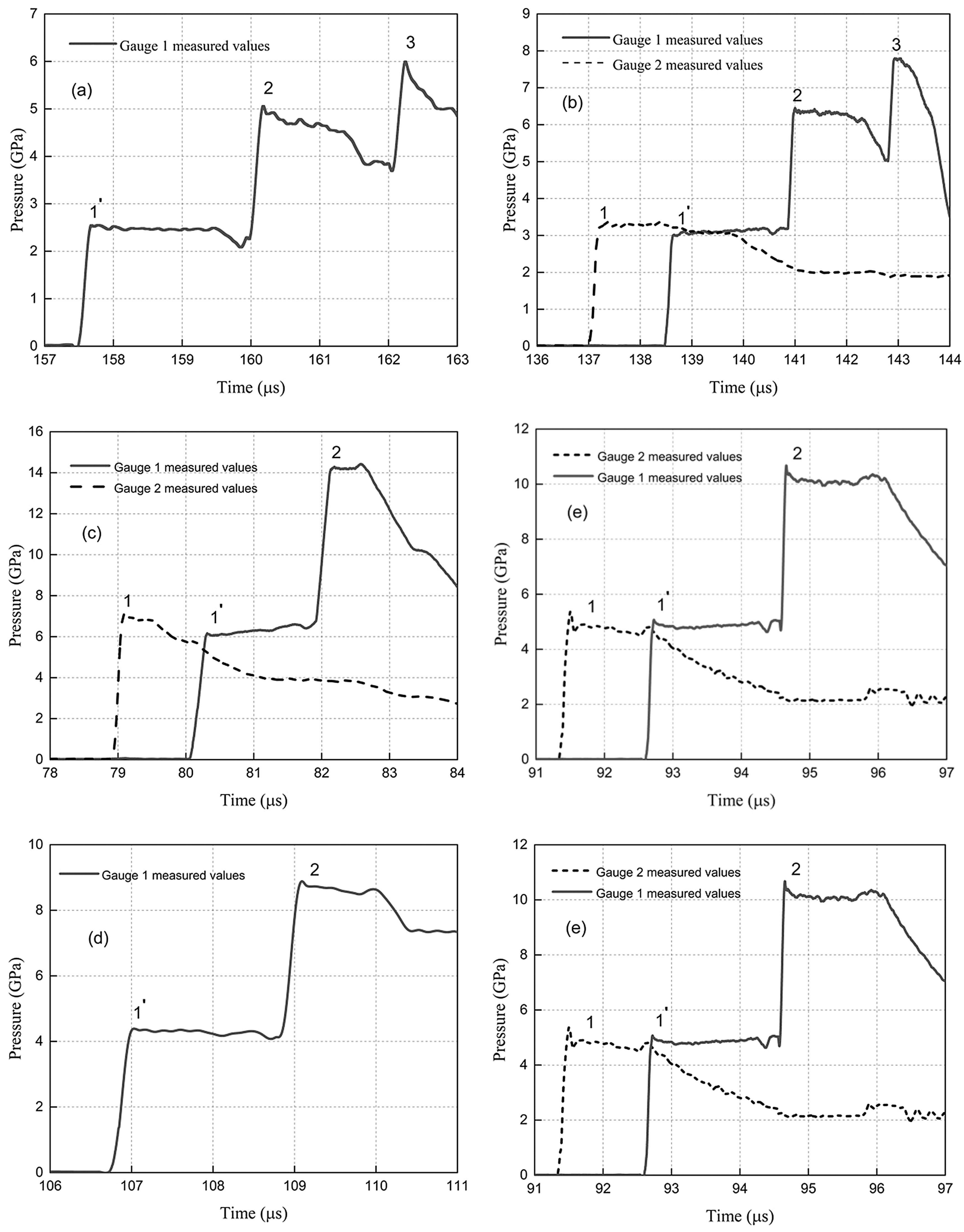

Figure 4. Observed pressure profiles recorded by PVDF gauges for (a) Shot 1, (b) Shot 2, (c) Shot 3, (d) Shot 4 and (e) Shot 5. The solid curves denote measurements from the gauge 1# and the dashed lines denote measurements from the gauge 2#. The corresponding initial impact velocities are listed in Table 2.

states $i = 2, 3$ are determined by the Hugoniot relation of explosive with graphic mirror method and the particle velocity relation in Eq. (9). The average deviation of pressure and interval time is about 11.85 %.

The impedance match solution uses the Hugoniot EoS of unreacted PBX, but reverberated states actually deviate from the Hugoniot states. Therefore, this method cannot describe the shock reverberation process correctly. It is nec-

Table 3. Comparison of the measured reverberated pressure and delta time with that calculated from the impedance matching method.

Shot No.	Shock state	Delta Time [μs] Measured	Calculated	Jump No.	Pressure [GPa] Measured*	Calculated	d
1	$\Delta t_{1-1'}$	/	/	P_1	/	2.784	0.0969
	$\Delta t_{1'-2}$	2.516	2.786	P_2	5.540	5.471	0.1086
	Δt_{2-3}	2.067	2.317	P_3	7.802	7.374	0.0580
2	$\Delta t_{1-1'}$	1.467	1.397	P_1	3.290	3.626	0.1053
	$\Delta t_{1'-2}$	2.365	2.615	P_2	7.337	7.184	0.0979
	Δt_{2-3}	1.944	2.146	P_3	9.981	9.607	0.1019
3	$\Delta t_{1-1'}$	1.208	1.157	P_1	6.881	7.224	0.0648
	$\Delta t_{1'-2}$	1.839	2.171	P_2	16.571	14.446	0.2122
4	Δt_{1-1}	1.324	1.280	P_1	/	5.087	0.0344
	$\Delta t_{1'-2}$	2.100	2.397	P_2	10.119	10.143	0.1240
5	$\Delta t_{1-1'}$	1.247	1.190	P_1	5.304	6.589	0.2008
	$\Delta t_{1'-2}$	1.974	2.229	P_2	12.448	13.172	0.1269

*modified by the damping factor

essary to use another EoS to describe the reverberated off Hugoniot states.

4.3 Mie-Grüneisen Equation of State

Using the Hugoniot relation of unreacted PBX as a reference curve, the expression of the Mie-Grüneisen EoS, can be derived as Eq. (14). The reverberated state i is then evaluated from the $i-1$ state. Combing the formulas based on conservation of mass, momentum as Eq. (2), (4), and the Mie-Grüneisen EoS, the relations among pressure, volume and Grüneisen parameter will be obtained. By comparing calculated results with the experimental pressures and interval times of reverberated states, the estimation error of each Grüneisen parameter can be determined. The pressure data in Shot 3 is removed since it is evidently beyond experimental error.

The measured values of jumps ($i = 1', 2, 3$) in each shot are used to compute the off-Hugoniot states. Figure 5 shows the average deviation from the experimental data versus the Grüneisen parameter Γ. The minimum error achieves at the best fitting Grüneisen parameter of . It is assumed that the Grüneisen parameter Γ is independent of volume.

Figure 6 (a) shows a pressure increasing process corresponding to the stepped pressure process records by gauge 1#. The three noted points can be considered as the three stable states after each shock wave (one initial wave and two reflected waves). Figure 6 (b) gives the locus of shock waves propagating within the explosive. Figure 6 (c) shows the gradual increasing shock wave velocity due to the compression of the sample for Shot 2. In Shot 2, the pulse-duration is about 4.65 μs which is shorter than the time of reflected shock wave arriving at the position of gauge 2#. It is verified by the missing of pressure stages in gauge 1# measurements.

Table 4 gives the calculated results using the Mie-Grüneisen EoS ($\Gamma = 1.3$). The average deviation is about 4.72 %. The calculated values are in good agreement with the

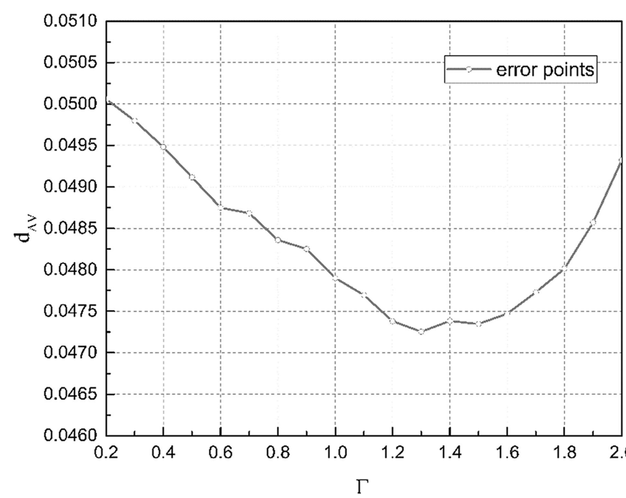

Figure 5. The relationship between average error d and Grüneisen parameter Γ.

measured stepped values and the deviation is lower than that calculated by the impedance matching method.

Thus, the Grüneisen parameter is not fixed at all conditions. It actually depends on the compressed volume. According to the direct expression by Huang [22]

$$\Gamma(\nu) = \frac{U_s^e\left(2U_s^e - C_e\right)\left[C_e + (S_e - 1)U_s^e\right] - U_s^e C_e\left(U_s^e - C_e\right)\Big/3 - S_e C_e^3}{U_s^e\left(U_s^e - C_e\right)\left(U_s^e + C_e\right)}, \tag{17}$$

its relationship with specific volume can be theoretically estimated from the initial Hugoniot states. Due to the approximately 3.5 % difference of specific volume between the two reflected states where the data we used to fit this parame-

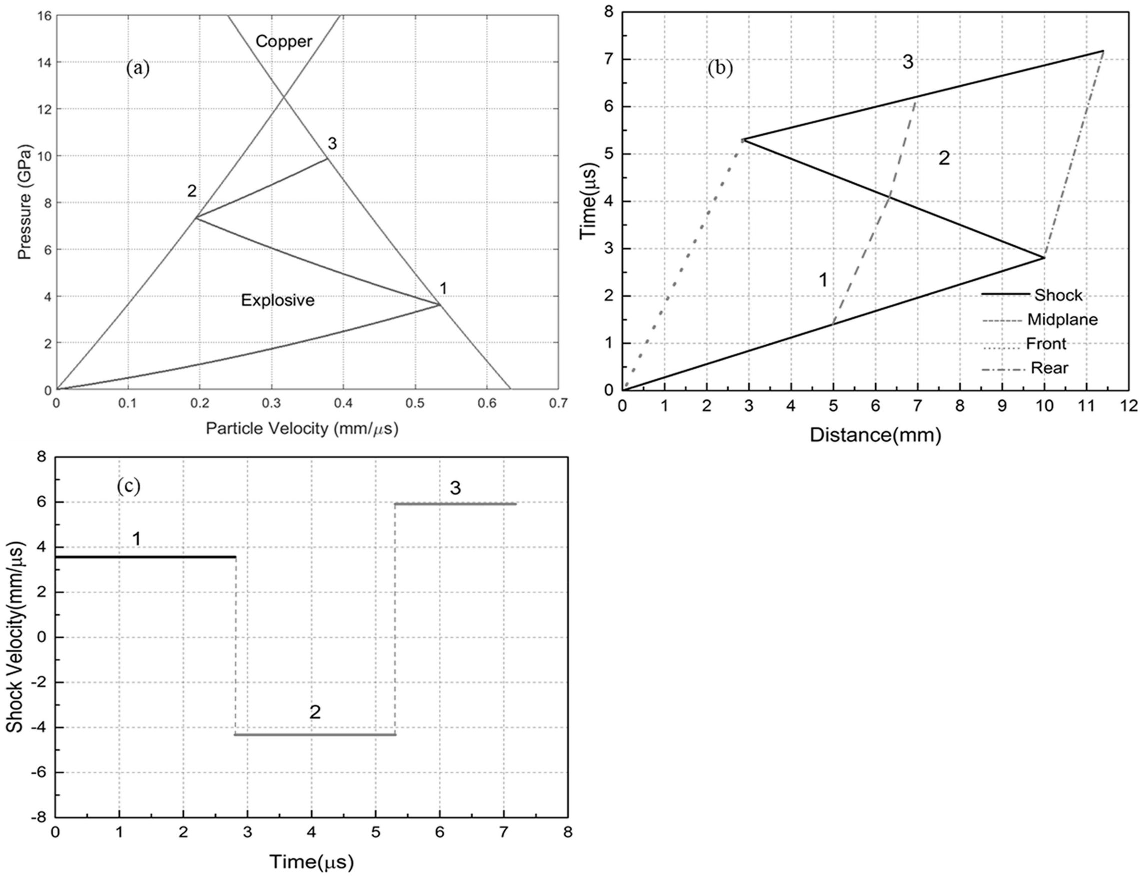

Figure 6. (a) Graphical representation of the impedance matching method for Shot 2; (b) The relationship between position and time for Shot 2; (c) The shock velocity varied with time in the explosive sample for Shot 2 using the Grüneisen parameter $\Gamma = 1.3$. The jump 1 represents the initial impact state, the jump 2 represents the state of shock wave is reflected from copper reflector and jump 3 represents the state of shock wave is reflected from copper delay.

Table 4. Comparison of the observed reverberated pressure and time with that calculated from the Mie-Grüneisen equation of state using $\Gamma = 1.3$ and the total deviation. P_2 in Shot 3 is not included in average due to evident difference of about 16% from experimental data.

Shot No.		Delta Time [μs] Measured	Calc.[a]	Calc.[b]		Pressure [GPa] Modified	Calc.[a]	Calc.[b]	d[a]	d[b]
1	$\Delta t_{1'-2}$	2.516	2.689	2.786	P_2	5.540	5.541	5.471	0.0643	0.1086
	Δt_{2-3}	2.067	2.080	2.317	P_3	7.802	7.520	7.374	0.0380	0.0580
2	$\Delta t_{1'-2}$	2.365	2.497	2.615	P_2	7.337	7.313	7.184	0.0530	0.0979
	Δt_{2-3}	1.944	1.876	2.146	P_3	9.981	9.853	9.607	0.0385	0.1019
3	$\Delta t_{1'-2}$	1.839	1.812	2.171	P_2*	16.571	14.310	14.446	0.0149	0.1529
4	$\Delta t_{1'-2}$	2.100	2.250	2.397	P_2	10.119	10.417	10.143	0.0725	0.124
5	$\Delta t_{1'-2}$	1.974	1.941	2.229	P_2	12.448	13.055	13.172	0.0495	0.1269
Average d[a] = 0.0472 Average d[b] = 0.1100										

[a] Calculated using the Mie-Grüneisen equation of state $\Gamma = 1.3$; [b] Calculated using the Hugoniot relation

ter from, there only can be a deviation smaller than 0.1 for the Grüneisen parameter. Such slight deviation will not induce any difference to the expression of the Mie-Grüneisen EoS and can be ignored in assumption.

Huang's equation gives an ideal Grüneisen parameter from the initial Hugoniot state. It can be simplified as a linear relation with specific volume when pressure is not too high ($v/v_0 < 1.4$). But this value is usually overestimated, especially for composite explosives. The accurate value of the Grüneisen parameter needs to be determined by experiments. The reverberation technique used in this work is such a convenient and efficient method, which was successfully applied to silicone elastomer [23]. This technique also can be used to yield high pressure environment and presents great potential in compression science [24].

5 Conclusion

Multiple reverberated shock compression process within unreacted explosive is investigated both experimentally and theoretically in this work. The reflected shock states generated from compressed states with finite shock velocity deviate from the general Hugoniot relation. The Mie-Grüneisen EoS is thus introduced to describe such dynamic continuous reverberated process. It has a better agreement with the experiments, compared to the approximated impedance matching method. The results of the Mie-Grüneisen EoS highly depend on the Grüneisen parameter of the material (unreacted TATB-based PBX in this work). According to this, we acquire the reliable Grüneisen parameter of $\Gamma = 1.3$ with a minimum error deviating from experiments. This work demonstrates that this reverberated shock technique can be an accurate and convenient approach to determine Grüneisen parameter of unreacted explosives and provides guidance for further research on both experiment and theory.

Acknowledgement

We thank the National Defense Science Foundation of China (Grant number: JSZL2016212 C001) and Science Challenge Project of China (Grant number: TZ2018001) for supporting this work.

References

[1] H. S. Dong, F. F. Zhou, *High-energy explosives and related properties*, Science Press, Beijing, **1989**.
[2] B. M. Dobratz, *The insensitive high explosive triaminotrinitrobenzene (TATB): Development and characterization*, *1888 to 1994*, Technical Report, Office of Scientific & Technical Information, Oak Ridge, TN, USA, **1995**.
[3] E. L. Lee, C. M. Tarver, Phenomenological model of shock initiation in heterogeneous explosives. *Phys. Fluids* **1980**, *23*, 2362–2372.
[4] C. W. Sun, Y. Z. Wei, Z. K. Zhou, *Applied Detonation Physics*, National Defence Industry Press, Beijing, **2000**.
[5] B. A. Nadykto, Equations of state of unreacted explosives: PETN, RDX, HMX, TATB, *EPJ Web of Conferences* **2010**, *10*, 00007.
[6] S. R. Menikoff, *Complete EOS for PBX 9502*, Technical Report No. LA-UR-06-06529, Los Alamos National Laboratory, Los Alamos, NM, USA, **2006**.
[7] W. C. Davis, J. R. Travis, Shock Initiation of Detonation in Liquid Explosives, *Phys. Fluids* **1961**, *4*, 498–510.
[8] X. Zhang, J. C. Chi, M. X. Feng, Hugoniot Relation of JB-9014 Insensitive High Explosive, *Chin. J. High Pressure Phys.* **2001**, *15*, 304–308.
[9] A. M. Milne, N. K. Bourne, J. C. F. Millett, On the Unreacted Hugoniots of Three Plastic Bonded Explosives, *14th Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter*, Baltimore, MD, USA, 31 July-5 August, **2005**, AIP Conference Proceedings 845, p. 175.
[10] S. Eliezer, A. Ghatak, H. Hora, *Grüneisen equation of state*, *Fundamentals of Equations of State*, *World Scientific*, New York, **2014**, 153–164.
[11] B. P. Zhang, Q. M. Zhang, F. L. Huang, *Detonation Physics*, The Publishing House of Ordnance Industry, Beijing, **2001**.
[12] S. P. Marsh, *LASL Shock Hugoniot Data*, University of California Press, Berkeley, **1980**.
[13] F. Q. Jing, *Introduction to Experimental Equation of State* (2nd ed), Science Press, Beijing, **1999**.
[14] K. Kondo, Y. Yasumoto, H. Sugiura, A. Sawaoka, Multiple shock reverberations in a layer structure observed by particle-velocity and pressure gauges, *J. Appl. Phys.* **1981**, *52*, 772–776.
[15] S. A. Sheffield, R. L. Gustavsen, R. R. Alcon, In-situ magnetic gauging technique used at LANL – method and shock information obtained, *11th Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter*, Snowbird, UT, USA, June 27–July 2, **1999**, AIP Conference Proceedings 505, p. 1043.
[16] C. M Tarver, J. W. Forbes, F. Garcia, P. A. Urtiew, Manganin Gauge and Reactive Flow Modeling Study of the Shock Initiation of PBX 9501, *AIP Conf. Proc.* **2001**, *620*, 1043
[17] E. R. Lemar, J. W. Forbes, D. G. Tasker, A. J. Bur, *Polyvinylidene Fluoride Transducer for Dynamic Pressure Measurements*, in: *Shock Waves in Condensed Matter*, Springer US, New York, **1986**, p. 503–508.
[18] J. M. Liu, X. Zhang, H. Pei, J. Shu, S. Qin, B. Zhong, R. Zhang, Measurement of Hugoniot Relation for JB-9014 Insensitive Explosive. *Chin. J. High Pressure Phys.* **2018**, *32*, 033202.
[19] A. C. Mitchell, W. J. Nellis, Shock compression of aluminum, copper, and tantalum, *J. Appl. Phys.* **1981**, *52*, 3363–3374.
[20] X. Zhang, Y. Wang, F. Zhao, et al. Experimental investigation of the reaction-build-up for plastic bonded explosive JOB-9003. *Matter and Radiation at Extremes* **2017**, *2*.
[21] C. S. Lynch, J. A. Charest, Practical considerations on the piezofilm gauge technique, *Shock Compression of Condensed Matter*, Elsevier, Amsterdam, **1991**, 901–904.
[22] Y. K. Huang, Direct Method of Calculating the Grüneisen Parameter γ Based on Shock-Wave Measurements of Metals, *J. Chem. Phys.* **1969**, *51*, 2573–2577.
[23] R. E. Winter, G.Whiteman, G. S. Haining, D. A. Salisbury, K. Tsembelis, Measurement of Equation of State of Silicone Elastomer. *AIP Conf. Proc.* **2004**, *706*, 679–684.
[24] M. D. Knudson, D. L. Hanson, J. E. Bailey, C. A. Hall, J. R. Asay, Use of a wave reverberation technique to infer the density compression of shocked liquid deuterium to 75 GPa, *Phys. Rev. Lett.* 2003, *90*, 035505.

Manuscript received: July 14, 2018
Revised manuscript received: July 14, 2018
Version of record online: November 15, 2018