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Ultrasonic Evaluation of the Impact Damage of Polymer Bonded Explosives

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Abstract: The damage properties of polymer bonded explosives under dynamic loading were studied by using ultrasonic evaluation. Explosive samples were damaged by a low-velocity gas gun at different impact velocities. Ultrasonic examination was carried out with a pulse through-transmission method. Spectra analyses were carried out by using fast Fourier transform. Characteristic ultrasonic parameters, including ultrasonic velocities, attenuation coefficients, spectra area and master frequency, were obtained. The correlation between the impact damage and ultrasonic parameters was analyzed. A damage coefficient D was defined by considering a combination of ultrasonic velocity and amplitude. The results show that ultrasonic parameters can be used to quantitatively assess the damage extent in impacted plastic bonded explosives.

Key words: polymer bonded explosives; impact damage; ultrasonic evaluation

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Polymer bonded explosives (PBXs) are widely used in both civil and military applications when very high performance is required. The formation of damage and its evolution under dynamic loading has long been a focus in the field of damage mechanics and material sciences. Microscopy is used to observe the microstructure of the damaged material under dynamic loading to understand the failure process[1,2]. Ultrasonic testing is an efficient and non-destructive method and has been widely used in the field of damage mechanics and material sciences. From ultrasonic signals, one can obtain some characteristic ultrasonic parameters, including ultrasonic velocity, attenuation coefficients, master frequency, etc. These parameters have certain correlations with the damage. Ultrasonic test has been used to determine the damage in rock under shock loading[3-5]. The present paper presents some preliminary results in the study of impact damage of PBX using ultrasonic evaluation, and defines damage D through ultrasonic parameters.

1 Materials and Impact Experiments

Hot pressed PBXN-5 was used in the experiment. PBXN-5 contained HMX 94.5%—95.0% and fluorin rubber 5.0%—5.5%. The pressing pressure was 200 MPa and temperature was 100 ℃, and pressing duration was 1.5 h.

In our previous work[6], a low-velocity gas gun with a gas buffer was used to induce impact damage in PBX. The gas buffer can noticeably extend the duration of dynamic loading and lower the peak pressure. In this case, usually the mild damage can be induced. To produce the more severe damage in PBX, the direct impact was applied in the present paper. Fig. 1 shows a recorded stress history of PBXN-5 sample impacted by an aluminum projectile at a velocity of 75.5 m/s with a gas buffer and at a velocity of 71.0 m/s without a gas buffer. The peak stress and

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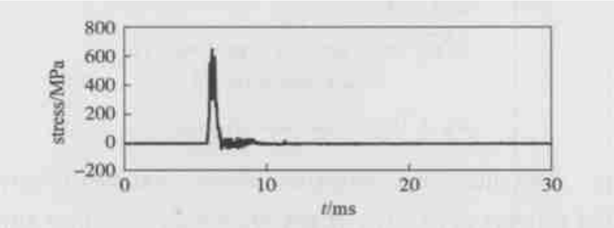
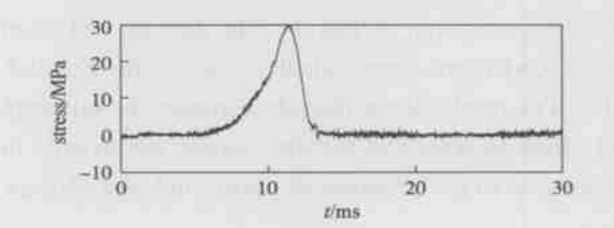
duration of stress impulse with a gas buffer are about 29.8 MPa and 8 ms respectively, compared with 644 MPa and 1 ms without a gas buffer. It is clearly shown that the presence of the buffer noticeably extends the duration and lowers the peak pressure.



(a) without a gas buffer



(b) with a gas buffer

Fig. 1 A typical stress history of impact loading

The experimental setup is shown in Fig. 2. A projectile impacts steel rod 2 directly and acts on the explosive sample. PBX samples were 20 mm in diameter and 10 mm in thickness. The sample was constrained in a steel tube. Two polyethylene cushions were placed between the explosive sample and two steel rods. The diameter and length of projectiles were 56 mm and 110 mm. Aluminum projectiles were used, and their weight was 0.72 kg. A stress gauge was mounted on steel rod 1 to measure the stress history during the impact. The impact velocities were controlled not to detonate the samples in order to recover the damaged samples and detect the damage in the samples.

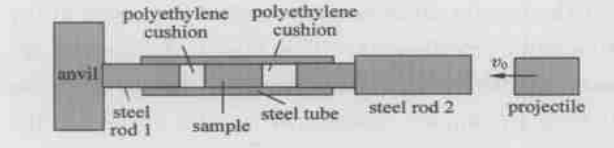


Fig. 2 Experimental setup of dynamic loading

2 Ultrasonic Testing and Analyses

2.1 Ultrasonic Velocities and Damage

The ultrasonic examination of damaged and undamaged samples was conducted by using a pulse through-transmission method, in which water was used as a coupling medium. The ultrasonic pulse velocity was obtained from the measured time delay Δt between the trigger signal corresponding to the pulse emission and the first received signal. The velocity of elastic longitudinal waves can be calculated as

$$c_{\mathrm{p}} = h/\Delta t, \tag{1}$$

where h is the thickness of the sample. Based on the measured velocities of elastic longitudinal waves of undamaged and damaged samples, the damage of samples can be calculated as

$$D = 1 - (c_{\mathrm{p}}/c_{\mathrm{p0}})^2, \tag{2}$$

where c_{p0} and c_{p} are the velocities of elastic longitudinal waves of undamaged and damaged samples respectively. Zhu Jinying et al.[7] proposed a definition of damage by considering the contribution of ultrasonic velocity, amplitude and frequency. In our experiment, the frequency was found insensitive to impact damage, so a combination of ultrasonic velocity and amplitude was considered to define damage, which can be expressed as

$$D = 1 - (\alpha_A \overline{A} + \alpha_v \overline{v}), \tag{3}$$

where α_A, α_v are weighted coefficients, $\alpha_A + \alpha_v = 1$; $\overline{A} = A/A_0$, $\overline{v} = v/v_0$, A_0, v_0 are the ultrasonic amplitude and velocity of the undamaged sample, A, v are the ultrasonic amplitude and velocity of the damaged sample.

2.2 Ultrasonic Attenuation

In ultrasonic attenuation tests, the incident signal, reflected signal and transmitted signal were first recorded. The attenuation coefficient was then calculated by

$$\alpha = \frac{20}{h} \lg\left[\left(\frac{A_{\mathrm{i}}}{A_{\mathrm{t}}} \times 10^{\frac{D_{\mathrm{t}} - D_{\mathrm{i}}}{20}} + \frac{A_{\mathrm{r}}}{A_{\mathrm{t}}} \times 10^{\frac{D_{\mathrm{t}} - D_{\mathrm{r}}}{20}}\right) \times \left(1 - \frac{A_{\mathrm{r}}}{A_{\mathrm{i}}} \times 10^{\frac{D_{\mathrm{i}} - D_{\mathrm{r}}}{20}}\right)\right], \tag{4}$$

where α is the attenuation coefficient of material; A_{i}, A_{t} and A_{r} are the amplitudes of incident waves, transmitted waves and reflected waves respectively; D_{i}, D_{t} and D_{r} are the magnification indexes of incident waves, transmitted waves and reflected waves respectively; h is the thickness of samples.

2.3 Frequency Spectrum Analysis

Frequency spectrum analyses of damaged and undamaged explosive samples were carried out by using FFT method, from which the master frequency and spectra area can be extracted.

3 Results and Discussion

Fig.3 shows the density decrease after the impact under different impact velocities. Due to the presence of microcracks and microvoids, the densities in damaged samples are reduced. The higher the impact velocity is, the more the density reduces. When the explosive samples are impacted by aluminum projectiles at speeds of 49.2, 62.9, 70.6 and 84.0 m/s, the densities after impact decrease by 0.911%, 1.017%, 1.182% and 1.406% respectively.

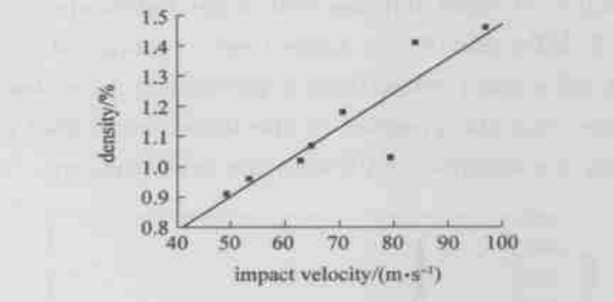


Fig. 3 Density decrease after impact

The ultrasonic velocities, attenuation coefficients and damage coefficient of the undamaged samples and the damaged samples impacted under different impact velocities are listed in Tab.1. The damage and attenuation coefficient were calculated by using Eqs. (2) (4). The results show that after impact the ultrasonic velocities decrease and the attenuation coefficients increase due to the presence of impact induced damage. In general, the lower the ultrasonic velocities, the higher the attenuation coefficients.

Tab. 1 Results of ultrasonic measurement

samples	impact velocity/ $(\mathrm{m \cdot s^{-1}})$	acoustic velocity/ $(\mathrm{km \cdot s^{-1}})$	damage D	attenuation coefficient/ $(\mathrm{dB \cdot mm^{-1}})$	spectrum areas S	main frequency f_0/kHz	amplitude A
undamaged	—	2.10	—	2.13	6 516.5	831	0.098
171	49.2	1.95	0.138	2.29	5 032.0	715	0.094
178	64.9	1.84	0.232	2.50	4 361.0	709	0.081
180	62.9	1.82	0.249	2.48	4 112.0	713	0.076
185	57.9	1.88	0.198	2.54	4 043.0	709	0.075
186	70.6	1.58	0.434	3.00	2 996.0	675	0.046
190	97.0	1.27	0.634	5.27	300.8	806	0.005
191	84.0	1.35	0.587	4.48	523.0	796	0.010
196	79.4	1.38	0.568	4.15	938.0	613	0.017

The relation between damage parameter D and attenuation coefficient α is shown in Fig.4. The relation with polynomial fitting can be expressed as

$$\alpha = A_1 + A_2 D + A_3 D^2, \tag{5}$$

where A_1, A_2, and A_3 are fitted parameters, $A_1 = 2.66$, $A_2 = -6.43$, $A_3 = 32.40$.

Frequency spectrum analysis is to disperse the wave signals received, and to calculate the valid wave parts reflecting explosive characteristics to obtain the spectra, so as to analyze the damage characteristics in the explosives. Based on frequency spectra analysis, the master frequency and spectra area can be obtained, which are listed in Tab.1. It is clearly shown that the spectra areas decrease with the increase of the attenuation coefficients. The master frequency appears insensitive to impact damage. In our previous study of the impact damage with a gas buffer[8], the correlation between master frequency and impact damage was not confirmed. In this experiment, the correlation between master frequency and impact damage seems to exist if the data of samples 190 and 191 are neglected. More experiments are needed to

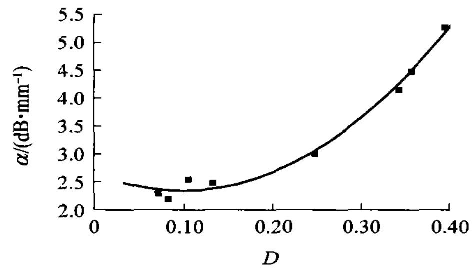


Fig. 4 The relation between damage parameter and attenuation coefficient

investigate the correlation between master frequency and impact damage.

The relation between spectrum area and attenuation coefficient is shown in Fig. 5 and the relation between amplitude and attenuation coefficient is shown in Fig. 6. Fig. 7 and Fig. 8 show the relations between spectrum area and damage, and the relation between amplitude and damage respectively. The results show that both attenuation coefficients and damage are inversely proportional to the spectrum area and amplitude. The results in Tab. 1 also show that the ultrasonic velocity is more sensitive than the master frequency, and the amplitude is the most sensitive ultrasonic parameter.

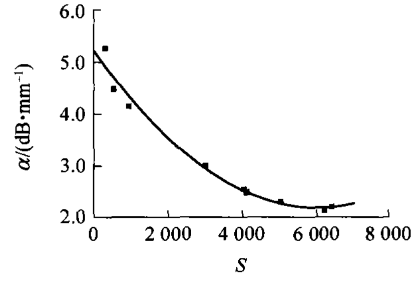


Fig. 5 Relation of spectrum area and attenuation coefficient

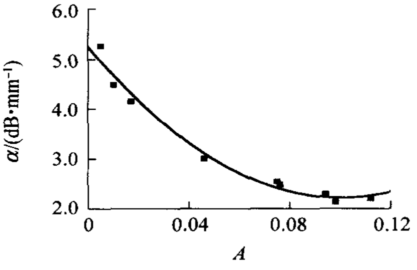


Fig. 6 Relation of amplitude and attenuation coefficient

The above results imply that the traditional definition of damage through only acoustic velocities is not accurate enough to assess the damage. The accurate assessment of damage through acoustic parameters should consider more parameters in addition to acoustic velocity. An attempt was made to use ultrasonic velocities and amplitude to define damage by using Eq. (3). Fig. 9 shows the relation between impact velocities and damage under different weighted factors. It is shown that the damage is largely influenced by the weighted factors. This new definition of damage provides more information and may access the damage state more accurately. In practice, a sensitive parameter can be assigned a large weighted factor. To determine the values of the weighted factors, more work needs to be done.

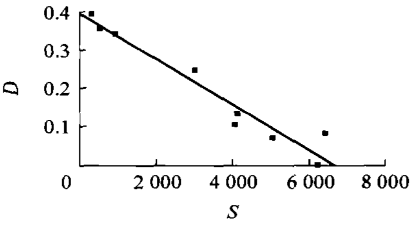


Fig. 7 Relation between spectrum area and damage parameter

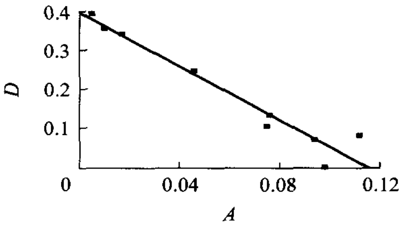


Fig. 8 Relation between amplitude and damage parameter

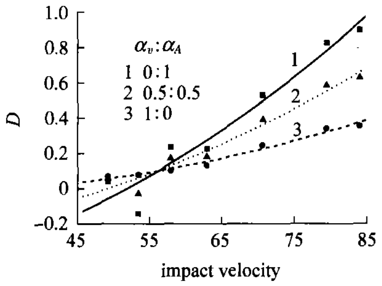


Fig. 9 Relation between impact velocities and damage under different weighted factors

4 Conclusions

Ultrasonic testing proves to be an efficient method in the study of the impact damage of explosive materials. It provides much useful information of damaged explosives including ultrasonic velocities, attenuation coefficients, spectra area and master frequency. The impact induces the damage in the explosive samples. In general, the higher the impact velocities, the lower the acoustic velocities and the larger the attenuation coefficients. Consistency exists between damage parameter and ultrasonic parameters including ultrasonic velocities, attenuation coefficients and spectra areas. Among the ultrasonic parameters, attenuation coefficient (amplitude) is the most sensitive one. More ultrasonic parameters should be taken into consideration to accurately assess the damage extent in explosives instead of using only ultrasonic velocities.

References:

[1] Wang Rangjia. Study on classification and dynamic elastic parameters in rock by sonic wave[M]. Beijing: Geological Publishing House, 1997. (in Chinese)

[2] Seamen L, Curran D R, Shockey D A. Computational models for ductile and brittle fracture[J]. J Appl Phys, 1976, 47(11): 4814—4826.

[3] Yang Jun, Gao Wenxue, Jin Qiankun. Experimental study on damage properties of rocks under dynamic loading[J]. Journal of Beijing Institute of Technology, 2000, 9(3): 279—284.

[4] He Hongliang, Ahrens T J. Mechanical properties of shock-damaged rocks[J]. Int J Rock Mech Min Sci & Geomech Abstr, 1994, 31(5): 525—533.

[5] Zhang Guanren. A note on fractal and shock sensitivities of condensed explosives[J]. Explosive and Shock, 1994, 14(2): 105—111. (in Chinese)

[6] Chen Pengwan, Ding Yansheng, He Songwei, et al. Experimental study on the impact damage of selected explosives[J]. Energetic Materials, 2003, 11(1): 13—17. (in Chinese)

[7] Zhu Jinying, Chen Longzhu, Yan Xishui. Ultrasonic pulses behavior in concrete during compressive loading [J]. Engineering Mechanics, 1998, 15(3): 111—117. (in Chinese)

[8] Dai Kaida, Chen Pengwan, Yang Jun, et al. Ultrasonic eualuation and fractal analyses of the impact damage of polymer bonded explosives[Z]. The 2003 International Autumn Seminar on Propellants, Explosives and Pyrotechnics, Guilin, 2003. (in Chinese)