Ultrasonic Evaluation and Fractal Analyses of the Impact Damage in Polymer Bonded Explosives*

DAI Kaida[1], CHEN Pengwan[1], YANG Jun[1], HUANG Fenglei[1] & DING Yansheng[2]
(1 State Key Laboratory of Prevention and Control of Explosion Disasters, Beijing Institute of Technology,
P O Box 327, Beijing 100081, China)
(2 Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China)

Abstract: The damage properties of polymer bonded explosives under dynamic loading were studied by using ultrasonic evaluation and fractal analysis. Explosive samples were damaged by a long-pulse low-velocity gas gun with a gas buffer under different impact velocities. The microstructures of the samples before and after impact were examined by use of polarized light microscopy. The optical micrographs were analyzed using image processing and fractal theory. Ultrasonic examination was carried out using a pulse through-transmission method. Spectra analyses were carried out using fast Fourier transform(FFT). Characteristic ultrasonic parameters including ultrasonic pulse velocities, attenuation coefficients, spectra area and master frequency were obtained. The correlation between the impact damage and ultrasonic parameters were analyzed. The results show that both ultrasonic parameters and fractal dimension can be used to quantitatively assess the impact damage of plastic bonded explosives.

Keywords: Polymer bonded explosives; impact damage; ultrasonic evaluation; fractal analysis

1 Introduction

Polymer bonded explosives (PBX) 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 fields of damage mechanics and material sciences. At present, various methods are available to measure the damage. Among them, ultrasonic testing is an efficient and non-destructive method and has been widely used in the field of damage mechanics and material sciences[1-3]. From ultrasonic signals, one can obtain some characteristic ultrasonic parameters including master frequency, ultrasonic velocity, attenuation coefficients, etc. These parameters have certain correlations with the damage. Many granular systems including PBX are fractal in nature. Fractal analysis can be used as a quantitative characterization method of the damage in explosives[4]. The present paper presents some preliminary results in the study of impact damage of PBX using ultrasonic evaluation and fractal analysis.

2 Experiment

Hot pressed PBXN-5 was used in the experiment. PBXN-5 contained HMX 94.5~95% and fluorin rubber 5.0~5.5%. The pressing pressure was 200MPa and the pressing temperature was 100℃. The pressing duration was 1.5h.

A low-velocity gas gun was used to induce impact damage in the experiments. To extend the duration of dynamic loading, a gas buffer was developed and installed on the gas gun. The duration of dynamic loading can be adjusted by filling the buffer with different pressure of gas. The duration of direct impact between two metal plates usually lasts only about hundreds of microsecond. However it can be extended to several milliseconds by use of a gas buffer[5].

The experimental setup is shown in Fig 1. PBX samples were 20mm in diameter and 10mm in thickness. A 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 record the stress history during impact.

---

* Project supported by the National Natural Science Foundation of China under contract 10002022.

The projectile firstly impacts the gas buffer, and then acts on the explosive sample via steel rod 2 ,and a polyethylene cushion.

Polarized light microscopy (PLM) was used to examine the microstructure of the samples before and after impact. The explosive samples were first ground using standard fine silicon carbide papers (800 grid) to obtain flat surfaces. Final polishing was carried out in an automatic polishing machine using 1 micron alpha alumina powder, at a load of 50 g, while being lubricated with distilled water. To avoid bringing additional unexpected damage to impacted samples in polishing, the explosive samples were first potted in commercial low-viscosity epoxide mounts with a traditional amine hardening agent and then cured. Fractal analyses were carried out based on the image processing of the micrographs.

Ultrasonic examination of damaged and undamaged samples was conducted using a pulse through-transmission method, in which water was used as a coupling medium. Ultrasonic pulse velocities and attenuation coefficients were calculated based on the ultrasonic signals. Master frequency and spectrum area were obtained by frequency spectra analyses using fast Fourier transform(FFT).

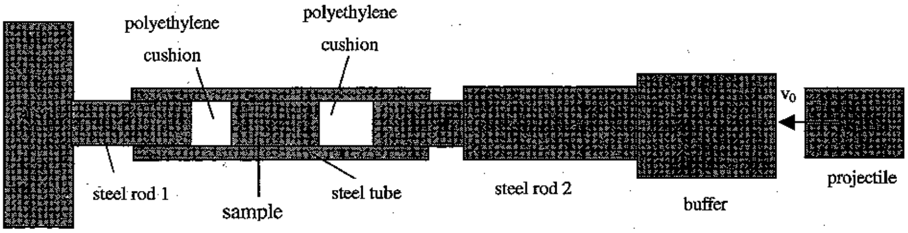

Fig.1 experimental setup of dynamic loading

3 Analyses of Ultrasonic Testing

3.1 Ultrasonic velocities and damage

The ultrasonic pulse velocity is 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 is then estimated as

$$C_p = \frac{h}{\Delta t} \tag{1}$$

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

$$D = 1 - \left(C_p / C_{p0}\right)^2 \tag{2}$$

Where C_{p0} and C_p are the velocities of elastic longitudinal waves of undamaged and damaged samples respectively.

3.2 Ultrasonic attenuation

In ultrasonic attenuation tests, incident signal, reflected signal and transmitted signal were first recorded. The attenuation coefficient is calculated as

$$\alpha = \frac{20}{h}\log\left[\left(\frac{A_i}{A_t}\cdot 10^{\frac{D_t-D_i}{20}} + \frac{A_r}{A_T}\cdot 10^{\frac{D_t-D_r}{20}}\right)\cdot\left(1-\frac{A_r}{A_i}\cdot 10^{\frac{D_i-D_r}{20}}\right)\right] \tag{3}$$

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 , D_r are the magnification indexes of incident waves, transmitted waves and reflected waves respectively, and h is the thickness of samples.

4 Fractal analysis

Many disordered systems have fractal in nature. Fractal geometry was first brought forward by Mandelbrot and has become a powerful tool in the study of irregular phenomena. It can be used to describe the local and overall self-similarity of irregular shapes. Fractal dimension is a major parameter of fractal geometry and can be used to quantitatively describe the extent of similarity. Fractal dimensions have been successfully used to study the microstructure of Al-alloy[6] and explosives[4].

Various methods can be used to define fractal dimensions, for instance, Hausdorff dimension, box counting dimension, self-similarity dimension and associated dimension. Box counting dimension is one of the most widely used methods. It can be defined as follows: if F is an arbitrary nonempty aggregate in R and has limited boundaries, and $N_\delta(F)$ is the smallest number of aggregates with the largest diameter and capable of overlaying F, the lower and upper box counting dimensions can be expressed as

$$\underline{\dim_B} F = \frac{\lim}{\delta \to 0} \frac{\log N_\delta(F)}{-\log \delta} \tag{4}$$

$$\overline{\dim_B} F = \overline{\lim_{\delta \to 0}} \frac{\log N_\delta(F)}{-\log \delta} \tag{5}$$

If these two values are equal, they are regarded as the box counter dimension of F

$$\dim_B F = \lim_{\delta \to 0} \frac{\log N_\delta(F)}{-\log \delta} \tag{6}$$

5 Results and Discussion

5.1 Ultrasonic tests

The ultrasonic velocities, attenuation coefficients and damage parameter of the undamaged samples and the damaged samples impacted under different impact velocities are listed in Table1. The damage was calculated using formula 2. The results show that after impact the ultrasonic velocities decrease and the attenuation coefficients increase due to the presence of damage induced by impact. In general, the lower the ultrasonic velocities, the higher the attenuation coefficients.

Table 1 Results of ultrasonic measurement

samples	impact velocity/ ($m \cdot s^{-1}$)	acoustic velocity/ ($km \cdot s^{-1}$)	damage D	attenuation coefficient/ ($dB \cdot mm^{-1}$)	spectrum area	main frequency f_0/kHz	amplitude $A(f_0)$
undamaged	--	1.92	--	2.43	6516.5	831	0.098
129	194.1	--	--	4.53	1134.6	756	0.017
130	60.4	1.74	0.1787	2.88	5538.7	834	0.086
131	147.8	1.70	0.2160	3.98	1978.3	775	0.029
132	191.4	1.65	0.2615	5.17	603.3	785	0.009
134	170.5	1.77	0.1501	2.72	6176.1	802	0.094

The relation between damage parameter D and attenuation coefficient α is shown in Fig.2. The relation with linear fitting is expressed as

$$\alpha = A + BD \qquad (7)$$

Where A and B are fitted linear parameters, $A = -0.98$, $B = 23.14$. The correlation coefficient reaches 98.2%, demonstrating that D and α have a satisfactory linear relation.

Frequency spectrum analysis is to disperse the wave signal 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. Fig. 3(a) shows the received transmitted ultrasonic signal of the undamaged sample. Fig.3(b) shows a typical transmitted ultrasonic signal of damaged samples. Fig.4(a) and Fig.4(b) show the frequency-amplitude and frequency-phase angle relations of the undamaged and damaged samples respectively, which were obtained from the frequency spectra analyses of Fig.3(a) and Fig.3(b). The master frequency and spectra area are listed in table 1. It is clearly shown that the spectra areas decrease with the increase of the attenuation coefficients. However the relation between frequency and attenuation coefficients is not certain. More experiments are needed to clarify this issue.

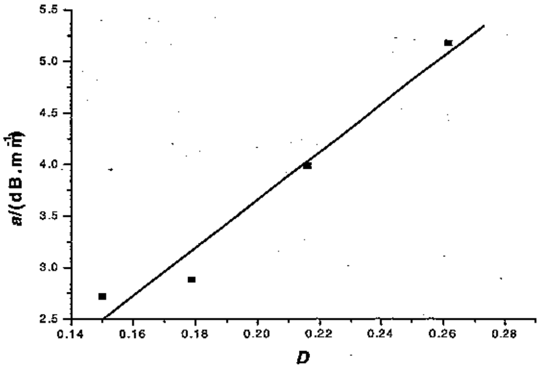

Fig.2 Relation of damage parameters and attenuation coefficients

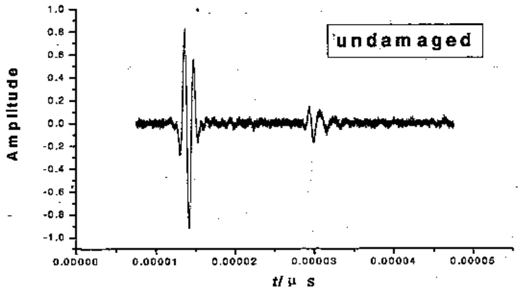

Fig.3(a) Transmitted ultrasonic signal of the undamaged sample

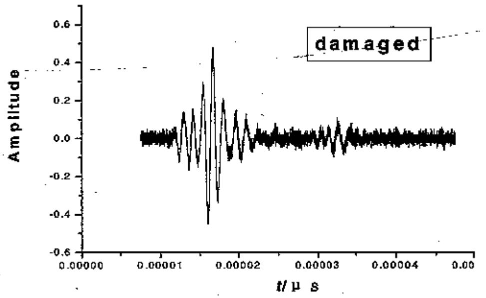

Fig. 3(b)Transmitted ultrasonic signal of the damaged sample

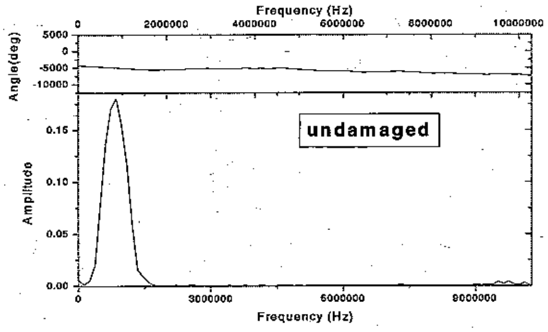

Fig. 4(a) The frequency-amplitude and frequency-phase angle relations of the undamaged sample

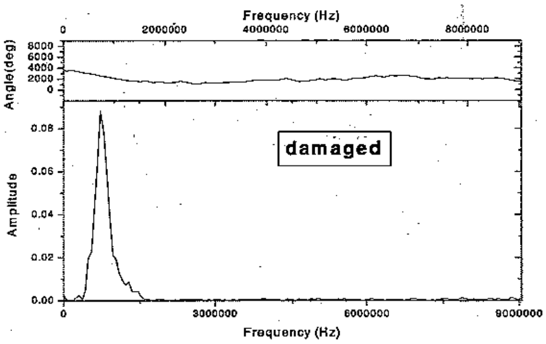

Fig. 4(b) The frequency-amplitude and frequency-phase angle relations of the damaged sample

The relation between spectrum area and attenuation coefficient is shown in Fig. 5. 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. It is shown that both attenuation coefficients and damage are inversely proportional to the spectrum area and amplitude, which can be explained as attenuation coefficients and dissipation of energy develop with damage evolution in damaged explosives. Their correlation coefficients exceed 97%. Thus the amplitude and spectrum area are regarded as the characteristic parameters of the stress wave traveling in the damaged explosive.

The results in Table 1 show that, among the ultrasonic parameters, amplitude and attenuation coefficient are more sensitive than ultrasonic velocities, and spectra area is the most sensitive ultrasonic parameter.

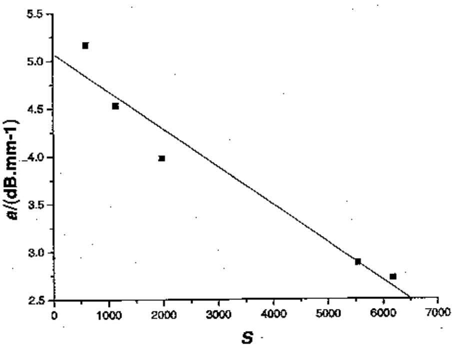

Fig. 5 Relation of spectrum area and attenuation coefficient

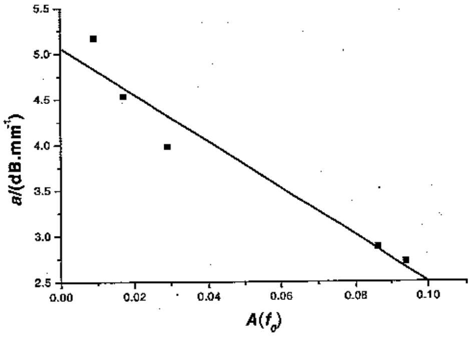

Fig. 6 Relation of amplitude and attenuation coefficient

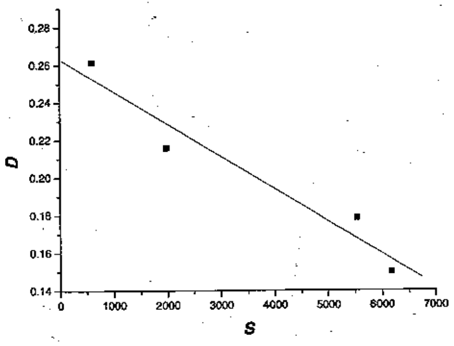

Fig.7 Relation between spectrum area and damage parameter

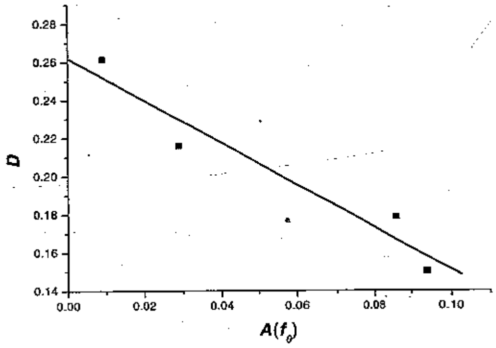

Fig. 8 Relation between amplitude and damage parameter

5.2 Fractal Analysis

Figs. 9~11 show the plan-view images of damaged PBXN-5 impacted at a speed of 109 m/s. Fig.9 is an image of near-field, while Fig. 10 and Fig. 11 are the images of mid-field and far-field respectively, with the projectile incident from right. A lot of microcracks are present in damaged samples. The mid-field and far-field regions show even more particle fractures than near-field region. In addition, a larger crack is present in mid-field region, showing coalescence of microcracks. The three micrographs are analyzed using an image processing application and box counting fractal theory. The values of fractal dimensions of the three micrographs are listed in table 2. Fractal dimensions reflect the extent of damage. The larger the fractal dimension, the more severe the damage in explosives. The fractal dimension of undamaged PBXN-5 is 1.2083, while it increases to 1.406, 1.416 and 1.450 in near-field, mid-field and far-field of damaged PBXN-5 respectively, demonstrating that impact

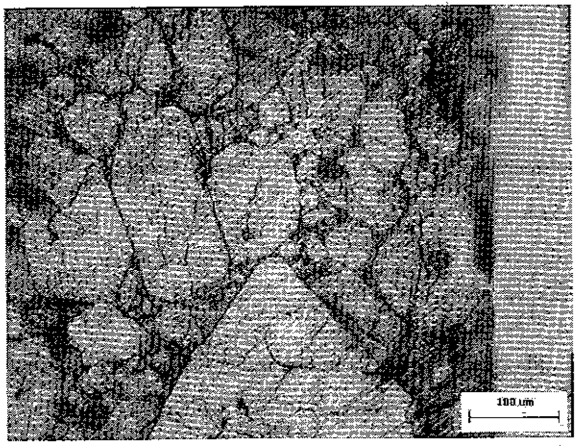

Fig. 9 Micrograph of damaged PBXN-5 in near-field region

induced damage is not homogenous in the sample, and the mid-field and far-field are more severely damaged.Our future work will expand to extensive fractal analyses of micrographs obtained under different impact velocities and investigate the correlation between ultrasonic assessment and fractal analysis.

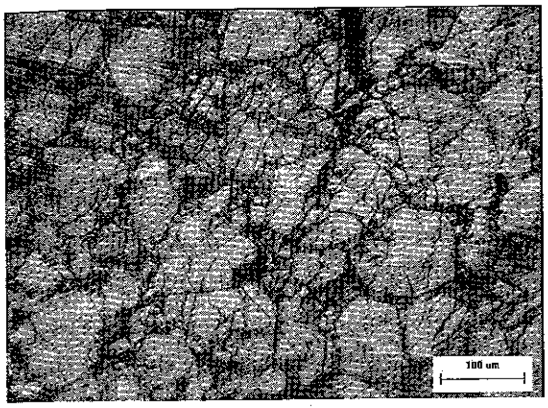

Fig. 10 Micrograph of damaged PBXN-5 in mid-field region

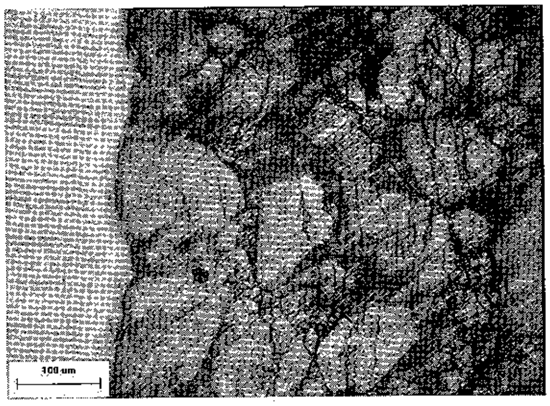

Fig. 11 Micrograph of damaged PBXN-5 in far-field region

Table 2 Fractal dimensions of undamaged and damaged PBXN-5

	undamaged	damaged		
		near-field	mid-field	far-field
D_f	1.2083	1.406	1.416	1.450

6 Conclusions

Ultrasonic testing and fractal analysis prove to be efficient methods in the study of the impact damage of explosive materials. Ultrasonic testing provides a lot of useful information of damaged explosives including ultrasonic velocities, attenuation coefficients, spectra area and master frequency. Among these ultrasonic parameters, attenuation coefficients are more sensitive than ultrasonic velocities, and spectra area is the most sensitive ultrasonic parameter. Spectrum area reflects the magnitude of ultrasonic wave energy, which indirectly reflects the energy dissipation of stress wave in the damaged explosive. Besides the ultrasonic velocities, more ultrasonic parameters should be taken into consideration in the assessment of damage extent in explosives. Fractal analyses show that the values of fractal dimensions are different in different regions of impact damaged samples, demonstrating that impact induced damage is not homogenous.

References

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

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

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

[4] Zhang Guanren. A note on fractal and shock sensitivities of condensed explosives. Explosive and Shock, 1994, 14(2): 105-111.

[5] Chen Pengwan, Ding Yansheng, He Songwei, et al. Experimental study on the impact damage of selected explosives. Energetic materials, 2003, 11(1): 13-17

[6] Ling Zhong, Bai Yilong. Study on the relation between fractal features of spalling surface and microstructures on an Al-alloy. Explosion and Shock Waves, 1994, 14(1): 2-8