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Mechanical properties characterization of Polymer bonded explosives based on Dynamic elastic modulus measurement†

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Abstract: In this paper, for nondestructive and quick investigation of the dynamic elastic modulus of PBX, a measurement system based on ultrasound velocity technique has been presented. The accuracy and reliability of the dynamic elastic modulus calculated by the velocity of ultrasonic longitudinal and transverse wave, which synchronizing received and transmitted by a new integrated sensor have been studied. Thermal cycling tests of different formulations of PBX, HMX and TATB based PBX, are undertaken at the range from -54～74℃. Dynamic elastic modulus is measured by the nondestructive measurement system to compare with static elastic modulus. The results show that dynamic elastic modulus, dynamic/static elastic modulus ratio reflect the difference of mechanical properties and material consistency. Dynamic elastic modulus quickly decreases to a low value and vibrates as the thermal cycling being in progress and mechanical properties decrease to a lower degree. After resting for a month, dynamic elastic modulus recovers in some degree along with mechanical properties. At preliminary stage of the thermal cycling, dynamic/static elastic modulus ratio increases and material consistency decreases, with micro-defects' initiation, as cracks and voids et. Along with the increase of the thermal cycling, dynamic/static elastic modulus ratio decreases on the contrary. PBX recovers consistency, with micro-defects' self-healing, in a lower level of mechanical properties.

Keywords: Polymer bonded explosives (PBXs); Dynamic modulus of elasticity; Ultrasound velocity; Thermal cycling test; Mechanical properties

1. Introduction

Polymer Bonded Explosives (PBXs) is a kind of important high-energy explosive, which is composed of high explosive crystal and polymer binder. Elastic modulus is a significant mechanical parameter of PBX, which used as a bridge between microstructure and macroscopical properties [1].

At present, the measurement methods of elastic modulus are mainly divided into two categories: static method and dynamic method. Static method is a method of destroying the specimen, and it does not have the chance to repeat the test. It has the disadvantages of large measurement error and limited specimen material such as metal and other ductile materials. The dynamic method is a nondestructive testing method that does not damage the structure and properties of the specimen. The specimen can be repeatedly tested. The dynamic elastic modulus of wood, concrete, rock and other materials measured by the dynamic method has a very significant linear correlation with the static elastic modulus measured by the static load method. The dynamic elastic modulus is often used to estimate the static elastic modulus of materials, or to directly evaluate the mechanical properties.

When measured by acoustic method, it is generally measured under very small stress and alternating load. The test results are higher than the results measured by the static method, that is, the elastic modulus of the stress-strain curve is equivalent to the time when the stress is near zero [2-7]. Under the general static load, the deformation, elasticity and plasticity of the material can be fully developed because the load is stable and the time is long. However, the dynamic load is not, of which the duration is short, or the size and direction periodically change, which makes the stress or the existence of a very short time disappearing, or constantly changing, equivalent to a repeated loading and unloading effect. The more discrete, granular and porous materials, the more elastic and plastic development lag behind the stress change, the deformation under the dynamic action is less than the static deformation and the dynamic elastic modulus is greater than the static deformation modulus. Conversely, the better the consistency of the material is, the closer the ratio of dynamic to static modulus is to 1.

In this study, the measurement of PBX dynamic elastic modulus based on the ultrasound velocity method is to measure the longitudinal wave velocity, the transversal wave velocity (known material density and thickness). The elastic modulus of a point on PBX can be measured quickly, lossless and accurately by the longitudinal and transverse wave integrated probe. It has a unique advantage over other methods of measuring elastic modulus. The thermal cycling tests of TATB based PBX and HMX based PBX are carried out at -54 ~ 74℃, and the changes of the dynamic modulus of elasticity, the modulus of static elastic modulus and the ratio of static and static elastic modulus of PBX are measured, and the modulus loss monitoring under the conditions of temperature and time load is realized. The results provide references for evaluating the mechanical properties and consistency of PBX under variable temperature conditions.

2. Materials and Methods

2.1. Ultrasound velocity method

According to the law of acoustic elasticity, the formula for calculating the ultrasonic velocity of longitudinal wave and transverse wave in infinite medium is:

$$V_L = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} \tag{1}$$

$$V_S = \sqrt{\frac{G}{\rho}} \tag{2}$$

In the form, E is the young's modulus, G is the shear modulus, σ is the Poisson's ratio, ρ is the density, V_L is the longitudinal wave velocity, V_S is the transverse wave velocity. In practice, the size of the medium is a certain size, which can’t satisfy the conditions of infinite solid medium. But when the size of the solid medium is much larger than the wavelength of the ultrasonic wave, it can be regarded as an infinite medium.

2.2 Dynamic elastic modulus measurement system

The hardware of the dynamic modulus measurement system is composed of computer, ultrasonic excitation receiver and ultrasonic sensor. The ultrasonic sensor is connected to the ultrasonic excitation receiver through the transfer line of the microdot to the lemon, and the ultrasonic excitation receiver is connected to the computer through the mini-USB data line. MISTRAS UTC110-4E ultrasonic stimulation receiving device is small in size and suitable for the system. It also has the function of excitation, reception and digital acquisition of ultrasonic signal. It is superior to 0.5MHz-25MHz, sampling frequency 100MHz, sampling precision of 12 bits, and can be used in parallel. The multi-channel ultrasonic signal excitation and receiving device can meet the above functions and technical requirements.

The ultrasonic sensor is an integrated 2.25MHz longitudinal and transverse wave probe by Institute of chemical materials, China academy of engineering physics, which integrates conventional longitudinal wave straight probe and conventional transverse wave straight probe, including sound absorbing materials, longitudinal wave piezoelectric wafers, transverse wave piezoelectric wafers, damping blocks, cables and shells, to achieve both longitudinal and transverse waves. Longitudinal wave and transverse wave vertical incidence is detected, as shown in Figure 1.

On the computer, the software of elastic modulus measurement is used to control the ultrasonic excitation receiver, and set up the ultrasonic parameters. The echo signal is transmitted back to the computer through the ultrasonic excitation receiver and the required data is read out to calculate the dynamic elastic modulus..

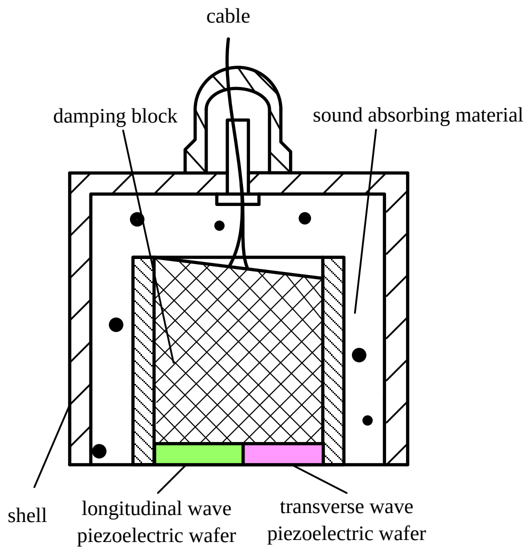


Figure 1. A new integrated ultrasonic longitudinal and transverse wave sensor

2.3 Specimens

PBX substitute materials, TATB based PBX substitute materials for purple, HMX based PBX substitute materials for green, respectively are machined to rectangular 1#~3# of length 100mm, width 100mm and thickness 10mm by Institute of chemical materials, China academy of engineering physics.

TATB based PBX is a polymer bonded explosive composed of TATB single explosive crystal and F2314 (Fluorine resin) binder. HMX based PBX is a polymer bonded explosive composed of HMX single explosive crystal, F2311 (Fluorine resin) binder and partial blunt explosive. They are machined to standard dumbbell 1#~11# of ø15mm ×102mm by Institute of chemical materials, China academy of engineering physics.

3. Results and Discussions

3.1 Measurement uncertainty of PBX dynamic modulus measurement system

The dynamic elastic modulus of PBX substitute material is measured by using a longitudinal and transverse wave integrated probe and a normal contact longitudinal wave probe and the transverse wave probe, and the uncertainty of measurement is given. According to the basic principle of the elastic modulus measurement of the ultrasound velocity method, to improve the accuracy of the measurement results of the elastic modulus, the measurement accuracy of the density, the longitudinal wave and the transverse wave velocity should be improved. The improvement of the measurement accuracy of the longitudinal wave and the transverse wave velocity must be achieved by increasing the measurement accuracy of the tested block thickness and time difference. The density and thickness of PBX can be less than 0.1% under conventional measurement methods. While the accuracy of time difference of ultrasonic propagation in PBX can be improved by increasing the sampling frequency, the average measuring value and the frequency of the probe. When the time difference is measured, the ultrasonic excitation receiving device with

100MHz sampling frequency is selected, and the time resolution is 10ns. After determining the above technical parameters, the measurement is done by the PBX substitute material to determine whether the measurement uncertainty of the system satisfies the requirements of the accuracy of analysis and measurement.

As an example of 1# HMX based PBX substitute materials, the thickness of the specimen is 10.04mm and the density is 1.81g/cm^3. Finally, the measurement value and the uncertainty of Yang's modulus of elasticity obtained the longitudinal and transverse wave integrated probe and the normal contact longitudinal wave probe and the transverse wave probe are E=13.16GPa, μ(E)=0.040GPa and E=13.32GPa, μ(E)=0.039GPa. The measurement value and the uncertainty of shear modulus of elasticity are G=5.36GPa, μ(G)=0.013GPa and G=5.53GPa, μ(G)=0.014GPa. The measurement results of the samples of 1#~3# green and purple PBX substitute samples show that the measurement uncertainty of the dynamic elastic modulus measurement system (random error, repeatability) is better than 0.5%.

3.2 Measurement reliability of the longitudinal and transverse wave integrated probe

The measuring results of the dynamic elastic modulus obtained by the longitudinal and transverse wave integrated probe and the normal contact longitudinal wave probe and the transverse wave probe are compared, and the measurement reliability of the PBX dynamic elastic modulus measurement system using longitudinal and transverse wave integrated probe is verified. There is a certain difference between the results of the longitudinal and transverse wave integrated probe and the longitudinal wave probe and the transverse wave probe (Young modulus <2.8%, shear modulus <4.8%).

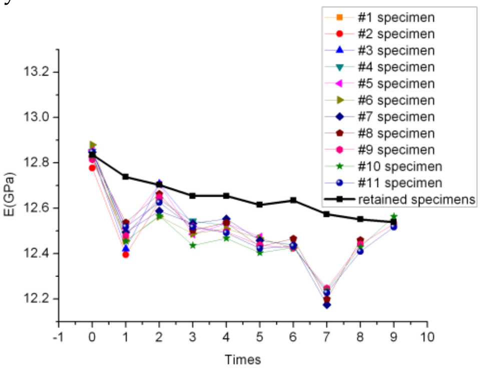
Table 1. Dynamic modulus of elasticity measurement results by different sensors

HMX based PBX substitute materials	**1#**		**2#**		**3#**	
	E(GPa)	**G(GPa)**	**E(GPa)**	**G(GPa)**	**E(GPa)**	**G(GPa)**
Integrated probe(k1)	13.16	5.36	12.40	5.05	12.53	5.09
Normal probe(k2)	13.32	5.53	12.47	5.19	12.62	5.23
(k1-k2)/k2×100%	-1.22%	-3.18%	-0.54%	-2.68%	-0.73%	-2.63%
TATB based PBX substitute materials	**1#**		**2#**		**3#**	
	E(GPa)	**G(GPa)**	**E(GPa)**	**G(GPa)**	**E(GPa)**	**G(GPa)**
Integrated probe (k1)	11.11	4.49	10.96	4.45	10.73	4.37
Normal probe (k2)	11.42	4.71	11.25	4.64	10.97	4.55
(k1-k2)/k2×100%	-2.76%	-4.74%	-2.59%	-4.25%	-2.17%	-3.92%

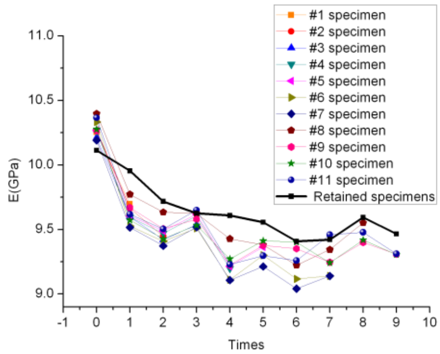
3.3 Dynamic and static elastic modulus during thermal cycling test

The dynamic elastic modulus of 1#~11# specimens of two formulations of TATB based PBX and HMX based PBX are measured during thermal cycling of different cycles. A thermal cycle is from room temperature to -40°C, then heating to +70℃, and finally cooling back to room temperature. The heating and cooling rate is 1℃ /min, heat preservation at high and low temperatures for two hours. This experiment consists of nine rounds, each having three thermal cycles. At the end of each round, one specimen is retained for follow-up experiments. The data show that the dynamic elastic modulus, the static elastic modulus and the dynamic and static modulus ratio vary with the PBX formula. The dynamic elastic modulus and the static elastic modulus of TATB based PBX are higher than HMX based PBX. The dynamic and static modulus ratio of TATB based PBX is lower than HMX based PBX. The mechanical properties and consistency of TATB based PBX are superior to HMX based PBX. The dynamic elastic modulus decreases with the increase of the aging cycles and oscillations near a low value, and the mechanical properties fall to a lower level. After a period of time, the dynamic elastic modulus increases and the mechanical properties recoveries, such as Figure 2, Table 2, and Table 3.

At the end of each round, one specimen of 1#~11# specimens of two formulations of TATB based PBX and HMX based PBX is retained and the others enter the next round. A month after the end of the thermal cycling test, the retained specimens of each round are taken out to dynamic elastic modulus and static elastic modulus measurement. The static elastic modulus is tested by quasi-static compression test and fitted by stress-strain relationship. According to the calculation of stress and strain, the ratio of dynamic and static modulus is the ratio between dynamic elastic modulus and static elastic modulus, as shown in Table 2 and Table 3. The data show that the ratio of dynamic and static modulus increases at the beginning of the thermal cycling test, the micro defects (holes, cracks, etc.) are produced, and the uniformity of material decreases. As the period increases, the ratio of dynamic and static modulus decreases, the micro defects self-healing, and the consistency of the material is restored at a lower mechanical performance.



(**a**)



(**b**)

Figure 2. Dynamic elastic modulus measurement during thermal cycling: (**a**) HMX based PBX; (**b**) TATB based PBX.

Table 2. Dynamic and static elastic modulus of HMX based PBX after thermal cycling rounds

Rounds	**ρ (g/cm³)**	**V_L (m/s)**	**V_S (m/s)**	**Ed (GPa)**	**Es (GPa)**	**Ed/Es**
0	1.847	2943.16	1654.79	12.836	11.37	1.129
1	1.840	2939.89	1651.18	12.738	11.09	1.149
2	1.839	2933.79	1649.98	12.703	11.01	1.154
3	1.837	2930.42	1647.54	12.654	11.05	1.145
4	1.836	2928.48	1647.57	12.654	10.98	1.152
5	1.836	2926.17	1645.52	12.615	10.70	1.179
6	1.835	2929.71	1647.09	12.634	10.87	1.162
7	1.834	2921.74	1643.93	12.573	10.87	1.157
8	1.833	2919.28	1643.09	12.551	10.94	1.147
9	1.833	2921.74	1642.59	12.551	11.05	1.136

Table 3. Dynamic and static elastic modulus of TATB based PBX after thermal cycling rounds

Rounds	**ρ (g/cm³)**	**V_L (m/s)**	**V_S (m/s)**	**Ed (GPa)**	**Es (GPa)**	**Ed/Es**
0	1.893	2707.33	1429.82	10.113	6.04	1.674
1	1.889	2654.96	1424.90	9.954	5.53	1.800
2	1.887	2618.75	1409.46	9.717	5.37	1.809
3	1.885	2596.82	1405.20	9.625	5.01	1.921
4	1.885	2596.35	1403.64	9.608	5.13	1.873
5	1.883	2584.06	1401.62	9.556	4.94	1.934
6	1.881	2565.91	1391.34	9.407	4.82	1.952
7	1.882	2562.30	1392.82	9.422	4.79	1.967
8	1.884	2581.36	1405.15	9.593	5.12	1.874
9	1.882	2564.89	1396.61	9.465	5.12	1.849

3. Conclusions

The measurement uncertainty (random error and repeatability) of PBX dynamic elastic modulus measurement system based on sound velocity method is better than 0.5%. There is a certain difference between the results of the longitudinal wave integrated probe and the longitudinal wave probe and the transverse wave probe (Young modulus <2.8%, shear modulus <4.8%). The dynamic modulus of elasticity, the static and static modulus and the modulus of elasticity vary with the PBX formula, and the dynamic elastic modulus and the static elastic modulus TATB based PBX are higher than the HMX based PBX, and the dynamic and static modulus of elasticity is lower than that of HMX based PBX, and the TATB based PBX mechanical properties and consistency are better than those of the HMX based PBX. The dynamic elastic modulus of the thermal cycle aging test decreases gradually with the aging period and is stable at a low value, and the mechanical properties decrease with the aging period. After a period of time, the dynamic elastic modulus increases and the mechanical properties pick up. In the early stage of the thermal cycling test, the ratio of static and elastic modulus increases, micro defects (holes, cracks, etc.) produce, and the uniformity of material decreases. As the period increases, the ratio of the modulus of elasticity and elasticity decreases, the micro defect self -healing and the material recovery at a lower mechanical performance.

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