Nonlinear ultrasonic testing technique for micro-damage of TATB based Polymer Bonded Explosive

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Abstract: The nonlinear ultrasonic testing technique for micro-damage of TATB based Polymer Bonded Explosive (PBX) components was researched on. A nonlinear ultrasonic testing experiment device was developed, as well as the characteristic signal extraction and processing method. The relation between the extent of the damage of PBX components and the nonlinear coefficient as well as wave distortion was obtained qualitatively, the feasibility of the detection of the micro-damage of PBX components by nonlinear ultrasonic was proved experimentally, which found a base to engineering applications such as damage identification, performance regression monitoring and lifetime prediction of the explosive parts.

Keywords: micro-damage, nonlinear ultrasonic, wave distortion, performance regression

Introduction

As a kind of insensitive and high energy explosive with good performance, Polymer bonded explosives (PBX) are wildly used in various weapons, and become the key part of the weapon, and operate as the functional materials and structural materials. Throughout the whole fabrication process of crystal preparation, particle coating, compacting, machining and heat treatment, PBX parts may take damages, such as incomplete coating of the binder, micro cracks, micro holes, particle cracking caused by extrusion between particles, partial desquamation of the binder and other initial damages[1~3]. ZHANG Wei-bin et al[2] used high performance industrial μCT to characterize and quantify the micro holes and damages inside explosive crystals, and revealed the existence of initial damage of the explosives; LI Jing-ming[4] used the Positron Lifetime Spectrum to get the conclusion that the heat treatment make the number of micro holes inside the TATB based PBX decrease while the size of them increase.

During long-time of storage, transfer and service, the initial damages assemble and expand continuously under the effect of heat and mechanical stress, making mechanical properties degraded and bearing capacity reduced, forming macroscopic cracks and fracture failure that affect the validity in usage and properties in service; on the other hand, the expansion of the damage and growing of the damage extent will make the hot spot sources of the explosives increased[5~7], affecting the detonation properties of the explosives and the safety and reliability of the weapon. Therefore the investigation of the characterization techniques of the initial damages such as micro cracks, micro holes, binder cracks and their extent is of great importance, that will play a important rule as technique support in the deep research of the effectivity, safety and reliability of the explosive parts of the weapon.

In war industry, it is a usual method to use ultrasonic non-destructive testing techniques to evaluate the defects inside explosive parts. For PBX parts, the linear wave theory based ultrasonic testing method such as the ultrasonic Pulsed Echo or transmission method are mainly used. Because of the limitation of the wave-length diffraction, only the macro defects such as cracks and delamination in millimeter magnitude that equivalent with the ultrasonic wavelength can be detected. For the micro damage in sub-millimeter or micron magnitude and its expansion, as well as the degradation in mechanical properties accompanied, the evaluation is not so efficient. Presently the non-destructive evaluation of the micro damage and its expansion of the explosive parts remains a challenging task.

Research shows the materials damage and property degradation are always accompany with some kind of non-linear mechanical behaviors, result in the non-linear ultrasonic transmission, such as the forming of the high-order harmonic wave[8~12]. The appearance of the tiny damages inside materials can be judged by these, firstly the metallic materials are investigated and positive progress are got. Damages of metallic materials and
degradation of their properties under conditions such as metal fatigue, stretching, and high-temperature creeping. Cantrell and Nazarov's research show properties' degradation of metallic materials after fatigue damage can be characterized by the non-linear coefficient. And some progress in theory have been made, such as line defect theory model, which explained the non-linear ultrasonic characters of materials in metallic micro-structure scale. These theories and experiments make up the classical non-linear ultrasonic wave theory of solid materials.

Recently the hot spot in research had turn to the non-linear ultrasonic characters of various composite materials, the researched scale is more extensive (10^{-9} \text{m} \sim 10^{-1} \text{m}). For example, in literature the dependence relations of fundamental wave and high-order harmonic wave formed by ultrasonic in rocks' materials with the acoustic source amplitude are investigated experimentally, and compared to the metallic materials, indicating non-linear solid materials like rocks show non-classical non-linear acoustic phenomenon different from classical non-linear acoustics.

According above stated, positive progress on the non-linear ultrasonic experimental and theoretical studies of the damage and property degradation of metallic materials and parts of non-metal materials was got home and abroad, providing a new way to study the damage and performance degradation of PBX materials. But until now, for PBX, a kind of heterogeneous explosives with highly packed crystal particles, the research on its damage characters by non-linear ultrasonic is still not reported. The non-linear ultrasonic techniques used in the research of micro-damage and performance of PBX parts can be meaningful, which will provide a new method for the evaluation of the micro-damage and its expansion regularity as well as the reliability of explosives storage.

1 Nonlinear ultrasonic testing device and its working principle

By using the Tektronix AFG3252 generator and TDS2048 type oscilloscope, and E&I A150 power amplifier, the nonlinear ultrasonic testing device was developed, as shown in Fig.1. The continuous sine wave or burst pulse strings of electronic signals with 2.5MHz frequency were produced by AFG3252 generator, and were amplified by A150 power amplifier. Then the high power (or limited amplitude) ultrasonic wave was transmitted into the PBX specimen through acoustic couplant from the transmitting transducer excited by the amplified electronic signals. The ultrasonic nonlinear effects such as high order harmonic or wave distortion were produced during the propagation of high power ultrasonic in PBX specimen included damage, and he nonlinear ultrasonic signals were received and transferred into electronic signals by the receiving transducer excited by the amplified signals. The time domain signals sampled by oscilloscope were transformed into frequency domain signals by Fast Fourier Transform (FFT), then the amplitude of fundamental harmonic and 2nd order harmonic could be obtained, and the nonlinear coefficient could be calculated by frequency domain signals according to the formulation 1.

\[ (a) \text{ a schematic of the nonlinear ultrasonic device} \quad (b) \text{ photo of the nonlinear ultrasonic device} \]
\[ \beta_i = \frac{8A_i}{k^2 x A_0^2} = \frac{2e^2 A_i}{\pi^2 f^2 x A_0^2} \]  

(1)

2 Nonlinear ultrasonic experiments

2.1 Experimental design

2.1.1 Experimental specimen

The TATB-based PBX was moulded forming into \( \Phi 20 \text{mm} \times 20 \text{mm} \) cylinder with different density by different moulding process, as shown in Fig.2, which was used as specimen.

![Fig.2 Size and density of TATB-based PBX specimen](image)

2.1.2 Loading damage of PBX specimen

There were various forms of damage of PBX materials such as granulation crushing, matrix cracking, micro-fissure and interface debonding etc, which would make the mechanical properties reduced. The most common practice of producing artificial damage was to use a compression or tension to the specimen. In this work, the compression fatigue loading tests under constant pressure were carried out on the TATB-based PBX specimen, so the damage degree could be characterized quantificationally relatively by using the cumulation fatigue cycles.

2.2 Experiment

Fatigue loading tests under constant pressure were carried out on the TATB-based PBX compression moulding forming specimen. Before and after the loading tests, the linear parameters such as gain and velocity were measured by using ultrasonic flaw detector, the waveform of being included nonlinear effect was sampled by using the developed nonlinear ultrasonic device. By FFT based on spectrum analysis method, the amplitude of fundamental harmonic and 2\(^{nd}\) order harmonic was obtained, and the nonlinear coefficient was calculated, by which the relationship between nonlinearity and fatigue damage was researched on.

3 Results and discussions

3.1 Damage identification for PBX by nonlinear ultrasonic coefficient

Based on uniaxial compression damage test for PBX specimen L1 with lower density and PBX specimen H1 with higher density, the compression strength is measured. Before the compression damage loading test, the linear parameters such as ultrasonic gain and velocity, and the nonlinear parameters such as the amplitude of fundamental harmonic and 2\(^{nd}\) order harmonic, as shown in Tab.1. After the damage loading test, the fracture topography is photographed, as shown in Fig.3.
Tab.1 Parameters test results of TATB-based PBX specimen L1 and H1

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Density /gcm$^{-3}$</th>
<th>Linear parameters</th>
<th>Nonlinear parameters</th>
<th>Compression breaking loading/N</th>
<th>Compression stress strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>1.887</td>
<td>46.6</td>
<td>-17.0</td>
<td>0.14254</td>
<td>106.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2106</td>
<td>-70.6</td>
<td>0.000295</td>
<td>5625</td>
</tr>
<tr>
<td>H1</td>
<td>1.910</td>
<td>14.2</td>
<td>13.0</td>
<td>4.466840</td>
<td>12.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2669</td>
<td>-33.4</td>
<td>0.021380</td>
<td>8500</td>
</tr>
</tbody>
</table>

Fig.3 Fracture topography of TATB-based PBX specimen with different density

Tab.1 showed that, the value of the nonlinear coefficient of TATB-based PBX specimen L1 with lower density is about 9 times more than the specimen H1 with higher density, by which we could infer that the specimen L1 has more damage than H1.

Fig.3 showed that, for TATB-based PBX specimen L1, there was intergranular craze in the fracture morphology, and the mould powder boundaries between with a lot of fissure and crack could be observed clearly. However, for TATB-based PBX specimen H1, it was transgranular craze with smooth fracture morphology. It could reflect that, the granular coated quality of specimen L1 is worth than H1, and the bonding strength between granular interfaces of specimen L1 was lower than H1, which resulted in that, the compression stress breaking strength of specimen L1(17.9MPa) was lower than H1(27.0MPa).

The compression breaking experiment and fracture analysis showed that, the initial damage and damage degree could be determined qualitatively and non destructively by the nonlinear ultrasonic coefficient.

3.2 Damage identification for PBX by wave distortion

With the action of limited amplitude ultrasonic, the damage interface contact status would be changed, and this change would in turn distort the ultrasonic waveform, which had been proved by experiment, as shown in Fig.4.
Fig. 4 showed that, for TATB-based PBX, the more the damage there was, the higher the nonlinear coefficient was and the more obvious the wave distortion was (or: more damage came with higher nonlinear coefficient and more obvious wave distortion.). From here we saw that the damage degree could be determined qualitatively by the wave distortion as well as the nonlinear ultrasonic coefficient.

3.3 Evaluation of the cumulation and development of damage of PBX by ultrasonic nonlinearity

The ultrasonic nonlinear parameters such as ultrasonic gain, velocity, and ultrasonic nonlinear coefficient in compression fatigue loading process was measured in order to study that, whether the cumulation and development of damage of PBX could be evaluated by ultrasonic nonlinearity.

The results of ultrasonic parameters of TATB-based PBX specimen L4 in the compression fatigue loading process were shown in Tab.2. The relation curves of ultrasonic nonlinear parameters such as gain and velocity and nonlinear coefficient vs cumulative fatigue cycles of specimen L4 was obtained, as shown in Fig.5. The photo of the surface crack and Computed Tomography (CT) image of the inner crack at cumulative 350 cycles fatigue loading was shown in Fig.6.

<table>
<thead>
<tr>
<th>Round</th>
<th>Cumulative fatigue cycles</th>
<th>Harmonic Fundamentals</th>
<th>Nonlinear parameters</th>
<th>Linear parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1st harmonic/A_0</td>
<td>-13.8 0.204174</td>
<td>Gain G/dB 38.0 2232</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nd order harmonic/A_1</td>
<td>-63.4 0.000676</td>
<td>Voltage V/m/s 258.60 59.4 2071</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
<td>1st harmonic/A_0</td>
<td>-22.6 0.074131</td>
<td>Nonlinear coefficient β_1×10^-9 221.55 55.2 2114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nd order harmonic/A_1</td>
<td>-73.8 0.000204</td>
<td>Gain G/dB 38.0 2232</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>1st harmonic/A_0</td>
<td>-24.9 0.056885</td>
<td>Voltage V/m/s 258.60 59.4 2071</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nd order harmonic/A_1</td>
<td>-80.1 0.000099</td>
<td>Nonlinear coefficient β_1×10^-9 221.55 55.2 2114</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>1st harmonic/A_0</td>
<td>-25.8 0.051286</td>
<td>Gain G/dB 38.0 2232</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nd order harmonic/A_1</td>
<td>-73.0 0.000224</td>
<td>Voltage V/m/s 258.60 59.4 2071</td>
</tr>
<tr>
<td>4</td>
<td>350</td>
<td>1st harmonic/A_0</td>
<td>-31.8 0.025704</td>
<td>Nonlinear coefficient β_1×10^-9 221.55 55.2 2114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nd order harmonic/A_1</td>
<td>-77.8 0.000129</td>
<td>Gain G/dB 38.0 2232</td>
</tr>
</tbody>
</table>

Fig.5 Variation relationship between linear/nonlinear ultrasonic parameter and fatigue cycle of PBX specimen L4.

Fig.6 Micro-crack occurred in the cylindrical surface of PBX specimen L4 at 350 fatigue cycles.
Fig.5 showed that, for PBX specimen L4, the ultrasonic nonlinear coefficient began increasing rapidly at cumulative 250 fatigue cycles, and at cumulative 350 fatigue cycles it reached a pinnacle with 10 times more than the initial coefficient before loading, which indicated that the damage had developed into a very high level being in conformity with the fact that there occurred some surface cracks and inner cracks as shown in Fig.6. From here we saw that the cumulation and development of damage could be reflected sensitively by the ultrasonic nonlinear coefficient. However, the ultrasonic linear parameters such as gain or velocity was not changed obviously during the whole fatigue cycle loading process even at cumulative 350 fatigue cycles while there occurred some obvious surface cracks and inner cracks as shown in Fig.6, which illuminated that ultrasonic linear parameters was not sensitive to cumulation and development of micro-damage, unlike ultrasonic nonlinear coefficient, which was very sensitive to that.

4 Conclusion

The application prospection of nonlinear ultrasonic testing technique is very wide. It’s possible that to develop engineering applications such as damage identification, performance regression monitoring and lifetime prediction of the explosive parts by research on nonlinear ultrasonic detection mechanism and microstructural evolution of PBX materials.

Based on the developed nonlinear ultrasonic experiment device, testing technique and signal analysis approach, we obtained qualitatively the relation between the extent of the damage of PBX components and the nonlinear coefficient as well as wave distortion, proved experimentally the feasibility of the detection of micro-damage of PBX components. However, this work only studied preliminarily the feasibility of the detection of micro-damage of PBX materials by nonlinear ultrasonic technique, which still require further research on experimental technique and mechanism theory in order to apply it actually to engineering practice.

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