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Deformation and Failure of Polymer Bonded Explosives

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Abstract: The deformation and failure of pressed polymer bonded explosives under different types of loads including tension, compression and low velocity impact are presented. Brazilian test is used to study the tensile properties. The microstructure of polymer bonded explosives and its evolution are studied by use of scanning electronic microscopy and polarized light microscopy. Polishing techniques have been developed to prepare samples for microscopic examination. The failure mechanisms of polymer bonded explosives under different loads are analyzed. The results show that interfacial debonding is the predominant failure mode in quasi-static tension, while extensive crystal fractures are induced in compression. With the increase of strain rate, more crystal fractures occur. Low velocity impact also induces extensive crystal fractures.

Key words: polymer bonded explosives; deformation; failure; microstructure; Brazilian test
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Polymer bonded explosives (PBXs) are highly particle filled composite materials comprised of crystals of a secondary explosive and a polymer binder. The study of mechanical properties of PBXs is of great importance in the design of compositions, life prediction and safety evaluation of PBXs. The study of the mechanical properties and failure mechanisms of PBXs has drawn tremendous attention in recent years[1,2]. Low strengths and safety concerns bring additional difficulties in preparing samples and conducting mechanical tests of PBXs. The Brazilian test, or the diametrical compression, in which a disc of material is loaded diametrically in compression, has been used to generate tensile stress and evaluate the tensile failure stress of a material without the inconvenience of uniaxial dumbbell testing[3-5]. Optical and electronic microscopy examinations are effective methods to study the explosive microstructure and its evolution and to reveal the mesomechanical deformation and failure mechanisms of explosive materials. Different microscopy methods including scanning electronic microscopy (SEM), environmental scanning electronic microscopy (ESEM)[6] and polarized light microscopy (PLM)[7] have been successfully used in this regard. The deformation and failure mechanisms of PBX under different types of loads including the quasi-static and dynamic Brazilian test, quasi-static uniaxial compression and low velocity impact have been investigated in this paper.

1 Experiments

Hot pressed HMX-based PBXN-5 was used in the experiments. PBXN-5 contains HMX 94.5%—95.0% and fluorin rubber 5.0%—5.5% by weight. Molding powder was pressed into different sizes of samples in steel dies. The pressing pressure and temperature were 200 MPa and 100 ℃. The duration of pressing was 1.5 h.

A Brazilian test apparatus was developed to study the tensile properties of PBXs, in which a CCD camera was attached to conduct real time microstructural examination of the explosive sample during loading.

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Fig. 1 shows the loading geometry of Brazilian test.

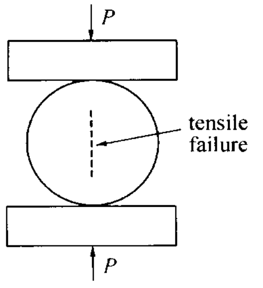

Fig. 1 Brazilian test geometry

The imposition of a compressive load, P, from the anvils on a disc of material causes a tensile failure on the vertical axis of loading. According to the simple elasticity theory, the maximum tensile stress at the center of the disc is given by

$$\sigma_x = \frac{2P}{\pi D t}, \qquad (1)$$

where D and t are the diameter and thickness of the sample respectively. The compressive stress at this point is approximately three times the tensile one.

Uniaxial compressive properties were also measured for comparison. Different strain rates were used in both Brazilian test and compression. To further investigate the influences of even higher strain rates on the deformation and failure of PBXs, the dynamic Brazilian test was conducted by using a drop weight to apply a dynamic load. In addition, a long-pulse low-velocity gas gun with a gas buffer was also developed and used to apply dynamic compression, through which the duration of dynamic compression can be extended to several milliseconds[8]. The explosive samples were confined in a steel tube during impact. The sample sizes were $\phi 10$ mm$\times$ 12 mm for the compression and $\phi 20$ mm$\times$ 10 mm for the Brazilian test and low velocity impact respectively.

Pre- and post-failure optical and electron microscopy examinations were conducted to reveal the microstructure of samples. In general, the failure occurs along the vertical axis in the Brazilian test, which brings convenience for real time examination of the microstructural evolution. Before loading the PBX samples, the images of central region were recorded. The load was applied by closing the Brizilian anvils up to approximately 80% the estimated failure value. This region was then re-examined. A further load was then applied until the first signs of failure appeared. At this point loading was stopped and the anvils held at constant separation as the cracks grew and the load relaxed. In this way, the initiation of failure and its evolution can be observed and followed.

In microscopic examination, the samples were first ground by using standard fine silicon carbide papers (800 grid) to obtain a flat surface. The final polishing was carried out in an automatic polishing machine with 1 μm alpha alumina powder, at a load of 50g, while being lubricated with distilled water.

2 Results and Discussions

Fig. 2 shows some tensile stress strain curves obtained by the Brazilian test under different strain rates, demonstrating that the tensile properties of PBXs are influenced by strain rates. At a strain rate of 8.33$\times 10^{-5}$ s^{-1}, the tensile failure stress and failure strain at the sample center are 0.85 MPa and 3.52$\times 10^{-3}$ respectively. The failure stresses were calculated by use of Eq. (1). While at a strain rate of 8.33$\times 10^{-4}$ s^{-1}, the failure stress and failure stain are 1.16 MPa and 2.85$\times 10^{-3}$. Fig. 3 shows some compressive stress strain curves of PBXN-5, demonstrating that the compressive properties of PBXs are also influenced by strain rates. The maximum stresses in the curves correspond to uniaxial compressive strengths. The compressive strengths increase with strain rates. At a strain rate of 6.94$\times 10^{-4}$ s^{-1}, the compressive strength is 9.8 MPa; while at a strain rate of 6.94$\times 10^{-2}$ s^{-1}, the compressive stress increases to 19.8 MPa. It is also shown that the strains corresponding to the maximum stresses do not change

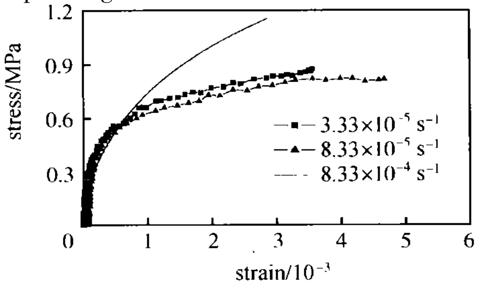

Fig. 2 Tensile stress strain curves

noticeably. Wiegand[9] reported similar results in the study of the compressive properties of PBXs and other explosives and proposed a failure criterion of constant critical strains for explosives and propellants.

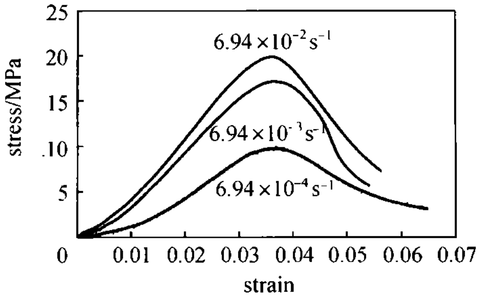

Fig. 3 Compressive stress strain curves

Tab. 1 lists the tensile and compressive strengths of PBXN-5 obtained in the experiments, demonstrating that the tensile strengths are much lower than the compressive strengths, less than one tenth of the compressive strengths. The microstructure of PBXs can account for this result. The explosive particles are separated in tension, so the binder plays a predominant role during deformation. While in compression the explosive particles are pressed and contacted with each other due to the extremely high volume faction of explosive crystals, so the explosive particles play a more important role during deformation. The above results demonstrate that PBXs have low strengths and low failure strains and their mechanical properties are strain rate dependent.

Tab. 1 Tensile strengths and compressive strengths of PBXN-5

strain rate/ s^{-1}	tensile strength/MPa	strain rate/ s^{-1}	compressive strength/MPa
3.33×10^{-5}	0.82	6.94×10^{-4}	9.8
8.33×10^{-5}	0.85	6.94×10^{-3}	17.1
8.33×10^{-4}	1.16	2.78×10^{-2}	18.1
—	—	6.94×10^{-2}	19.8

The real time microscopic examination of the Brazilian test revealed that the failure first started at several independent sites, usually around the boundaries of the larger HMX filler particles and formed microcracks. These microcracks linked up into larger cracks and finally induced the rupture of the samples. The initial damage such as debonding and uncoating generated during hot pressing are the origins of failure. Fig. 4 shows that a crack is extending along the boundaries of larger particles. Fig. 5 shows some extended binder filaments bridging the crack surfaces, demonstrating that the binder undergoes considerable deformation. The plan views of the fracture routes showed that the crystal fracture was very rare, but may appear due to the orientation of some larger particles perpendicular to an advancing crack path.

Fig. 4 Cracks expanding along particle boundaries

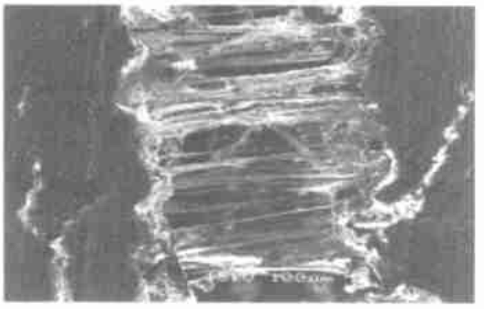

Fig. 5 Extended binder filaments bridging crack walls

The fracture surfaces in the Brazilian test were rough, with some partiles completely pulled out. The larger particles exhibited clean crystal faces due to the debonding of binder from particles. In contrast, the finer particles appeared rough having binder fibrils fractured due to extensive deformation. Fig. 6 shows a typical fractograph of PBXN-5 under the Brazilian test, in which both clean crystal surfaces and binder filaments can be observed. Though crystal fracture rarely occurs, it can also be found (see Fig. 7). The examination of fracture surfaces also showed that the failure predominantly followed the boundaries of the explosive fillers due to interfacial debonding with few fractured crystals. Some microcracks can also be observed on some particles (see Fig. 6). Due to the low stress amplitude applied in the Brazilian test, it is reasonable to assume that these microcracks were caused during pressing. The pressing pressure was 200 MPa, which was high enough to cause extensive fracture of explosive particles. To investigate the influences of pressing on the microstructure of explosive particles, the pressed PBX samples were soaked in a solution, e.g. iso-methyl butyl ketone, for enough time to totally remove the binder and leave the explosive particles alone, and then the obtained explosive particles were examined by SEM. The results showed the presence of the extensive fracture of particles and a lot of microcracks[8].

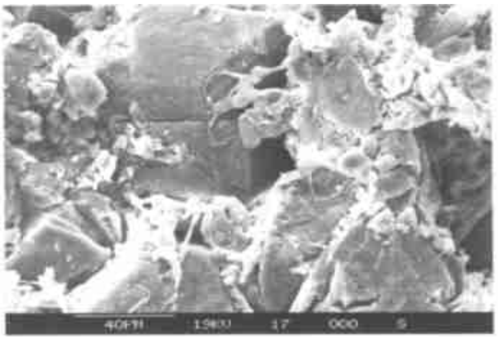

Fig. 6 A typical fractograph of PBX under Brazilian test

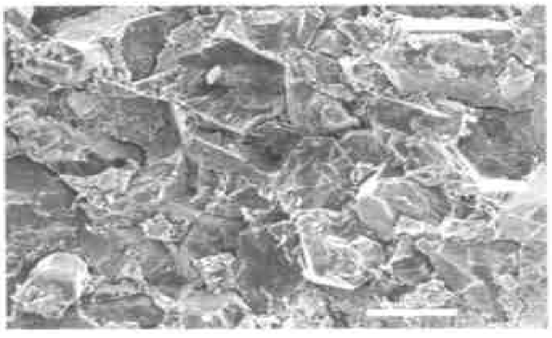

Fig. 7 Crystal fracture in PBX under Brazilian test

Fig. 8 shows a typical fractograph of a PBX simulant composed of 95% inorganic particles and 5% binder by weight. The fracture surface of the simulant is flatter than that of PBXN-5, and the failure is predominately due to crystal fractures instead of interfacial debonding. The PBX simulants usually are designed to simply simulate certain macroscopic mechanical properties of PBXs such as strengths, elastic modulus, etc. The present results demonstrate that the PBX simulants may not be able to sufficiently simulate their mesomechanical properties due to the differences between inorganic particles and explosive crystals.

The microscopic examination of the PBX samples fractured under higher strain rates in the quasi-static Brazilian test showed that with the increase of strain rates more crystal fractures occurred. To further investigate the influence of even higher strain rates, the dynamic Brazilian test was conducted, in which the sample disc was loaded by a drop weight and the corresponding strain rate was estimated as $0.3\times 10^{2}\ s^{-1}$. Fig. 9 shows a typical fractograph of PBX under the dynamic Brazilian test, demonstrating the presence of extensive crystal fractures.

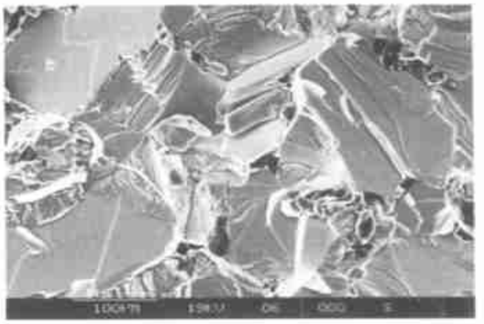

Fig. 8 A typical fractograph of a PBX simulant under Brazilian test

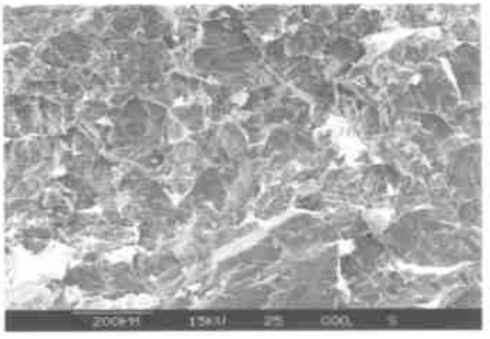

Fig. 9 A typical fractograph of PBX under dynamic Brazilian test

Fig. 10 shows a typical fractograph of PBXN-5 in the quasi-static compression test. The extensive crystal fractures can be observed, causing the formation of a large number of smaller particles. The corresponding tensile failure stress in the Brazilian test and the compressive failure stress in the compression test were estimated as 0.8 MPa and 8.8 MPa respectively, revealing that explosive particles with initial microcracks caused by pressing may not fracture under a tensile stress of 0.8 MPa, while may fracture under a compressive stress of 8.8 MPa.

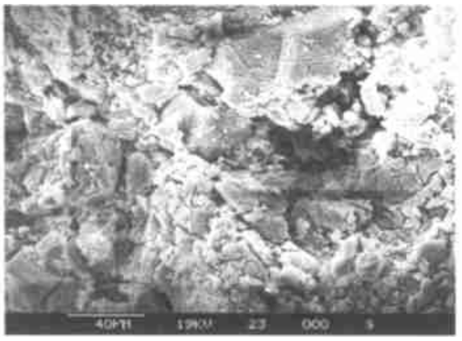

Fig. 10 A typical fractograph of PBX under compression

Fig.11 shows a plan view of PBXN-5 damaged by a steel projectile at an impact velocity of 108 m/s. The impact direction is from the right of the figure. The impact induced a large number of microcracks in explosive crystals. A vertical crack across explosive crystals can also be observed. At this impact velocity, no fragments were observed in PBXN-5 samples; however at the same velocity, the Composition B (containing TNT 40% and RDX 60% by weight) was severely fragmented. This demonstrates that despite the low concentration of binder, PBXN-5 exhibits better resistance to impact loading than the Composition B.

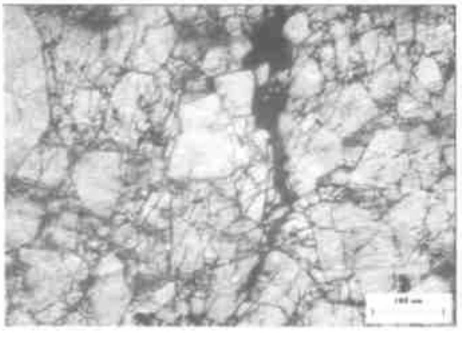

Fig.11 Microstructure of PBX damaged by impact

3 Conclusions

PBXs are brittle materials with low strengths and low fracture strains. The tensile strengths of PBXs are much lower than the compressive strengths, less than one tenth of the compressive strengths. Different failure modes correspond to different loading conditions. Interfacial debonding is the predominant failure mode in the quasi-static Brazilian test, and the crystal fracture is very rare. In the Brazilian test, the initial failure tends to start around the edges of the larger filler particles and often occurs at several independent sites simultaneously. The increase of strain rates causes more explosive crystals to fracture. In the dynamic Brazilian test, the predominant failure mode is crystal fracture. Extensive crystal fractures are also present in compression. The low velocity impact also induces extensive crystal fractures.

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