An Experimental Study on the Impact Damage of Explosives*

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Abstract: Damage not only deteriorates the mechanical properties of explosives, but also influences the sensitivity, combustion and even detonation properties of explosives. The study of formation mechanisms and evolution rule of damage, and the influences of damage on explosives is of great importance for safety evaluation of explosive materials. An experimental study of impact damage in cast Composition B and hot pressed PBXN-5 is presented in this paper. A long-pulse low-velocity gas gun with a gas buffer is used to induce dynamic damage in samples. The projectile velocities and stress history in impact loading are recorded. The microstructure evolution before and after impact are examined by use of Scanning Electronic Microscopy (SEM) and Polarized Light Microscopy (PLM). In addition, the densities and ultrasonic attenuation of undamaged and damaged explosives are measured. The results show that both Composition B and PBXN-5 exhibit brittle damage characteristics. However, due to the difference in compositions, PBXN-5 exhibits better resistance to dynamic loading than Composition B.

Key words: explosives; damage; low velocity impact; microstructure

1 Introduction

The responses of energetic materials and inert materials to external solicitations are quite different. The mechanical, thermal and chemical responses of energetic materials to external solicitations are usually coupled and complex. Damage not only deteriorates the mechanical properties of energetic materials, but also influences the sensitivity, combustion and even detonation behavior. It is believed that initiation originates from so-called hot spots formed due to the existence of various kinds of defects such as microcracks and microvoids. The study of the formation mechanisms and evolution rule of damage is of great importance for the prediction of mechanical properties and safety evaluation of energetic materials.

Explosives may be subjected to different forms of loads in transportation, storage, launching, penetrating, et al. Impact is one of the most common and dangerous load. Impact damage is closely related to the formation of hot spots under impact loading and its study has drawn tremendous attention from researchers across the world. Various equipment can be used to study impact damage and dynamic mechanical properties of explosives. Drop weight can be used to produce damage under median level strain rate [1]. The damage produced under high strain rate can be achieved using high-speed projectiles and flying plates [2-4]. The low strengths and risks of combustion and explosion bring additional difficulties to the study of mechanical damage of explosive materials. Correspondingly the loading equipment and analysis methods for explosives are different from those for inert materials. In this paper, a long-pulse low-velocity projectile with a gas buffer is used to apply dynamic loading and induce impact damage. The explosives used include cast Composition B and a hot pressed plastic bonded explosive (PBX). Microscopic examination, density and ultrasonic attenuation measurement are carried out to characterize the damage state in explosives.

2 Experiment

Cast Composition B and hot pressed PBXN-5 are used in the experiment in order to evaluate the influences of composition and shaping methods. Composition B contains: TNT 40% and RDX 60%. PBXN-5 contains: HMX 94.5~95% and fluorin rubber 5.0~5.5%. The pressing pressure and temperature are 200MPa and 100 ℃ and the time duration of pressing is 1.5h.

The gas gun used in our experiment is developed to apply long-pulse dynamic loading. The diameter of the gas gun is 56 mm. To extend the time duration of dynamic loading, a gas buffer is developed and installed on the gun. The time duration of dynamic loading can be adjusted by filling the buffer with different pressure of gas. The

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time duration of direct impact between two metal plates usually lasts only about hundreds of microseconds. However this can be extended to several milliseconds by use of a gas buffer. The impact velocities are controlled not to detonate the samples in order to examine the evolution of microstructure.

Fig. 1 is a schematic of impact loading. The sample is constrained in a steel tube. Two polyethylene cushions are placed between the explosive sample and two steel rods. The diameter and length of projectiles are 56 mm and 110 mm. Both steel projectiles and aluminum projectiles are used. The weight of a steel projectile and an aluminum projectile are 2 kg and 0.72 kg respectively. A stress gauge is mounted on steel rod 1 to measure the stress history during impact. The sample sizes for PBXN-5 and Composition B are $\phi 20\text{mm} \times 10\text{mm}$ and $\phi 20\text{mm} \times 20\text{mm}$ respectively.

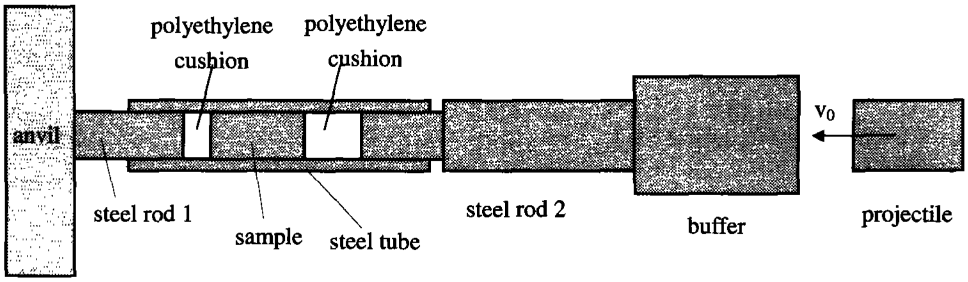

Fig.1 Schematic of dynamic loading

Different methods are used to characterize impact induced damage. The sample densities before and after impact are measured by using Archimedes method. Scanning Electronic Microscopy (SEM) and Polarized Light Microscopy (PLM) are used to examine the microstructural evolution under impact loading. An explosive usually has an exceptionally low toughness. Palmer and Field[5], for instance, quote a toughness of 0.05 MN.m$^{-3/2}$ for PBX9501, four orders of magnitude smaller than typical engineering alloys. In addition, explosive materials have risks of combustion and explosion. These bring difficulties to the preparation of microscopic samples. In our experiment, samples are first ground using standard fine silicon carbide papers (800 grid) to obtain flat surface. Final polishing is 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, samples are first potted in commercial low-viscosity epoxide mounts with traditional amine hardening agent and then cured. To better reveal the details of the microstructure, iso-methyl butyl ketone is selected to etch the surface. The polished and etched samples are directly used for PLM examination, while they have to be coated with a thin layer of gold for SEM examination. The whole polishing process can be monitored by using a CCD camera. To avoid the accumulation of friction heat and causing fatal accident in the polishing process, continuous distilled water is required to cool the samples. Fig. 2 shows a schematic description of an impact damaged sample. Three representative fields, including near-field (A), mid-field (B) and far-field (C), are chosen for examination.

Ultrasonic attenuation is measured before and after impact by use of pulse through-transmission method[6], in which water is use as a coupling medium. The attenuation coefficient is calculated as

$$\alpha = \frac{20}{D}\left[\log\frac{A}{A_0} - \log\frac{(\rho c + \rho_w c_w)^2}{4\rho c \rho_w c_w}\right] \tag{1}$$

where α is attenuation coefficient, D is the thickness of samples, A_0 and A are the amplitude of ultrasonic wave pulse before and after inserting samples into water, ρ and c are the density and sound velocity of samples, ρ_w and c_w are the density and sound velocity of water.

3 Results and discussion

Fig. 3 shows a recorded stress history of PBXN-5 sample impacted by a steel projectile at a velocity of 109 m/s. The peak pressure and time duration of stress impulse are about 264 MPa and 3 milliseconds respectively. It is clear that the buffer plays an important role in extending the duration time one order higher than usual. Fig. 4 is a micrograph of undamaged PBXN-5, showing some microcracks in explosive particles as a result of hot pressing. Figs. 5 ~ 7 are plan-view images of damaged PBXN-5 impacted at a speed of 109 m/s. Fig. 5 is an image of near field, while Fig. 6 and Fig. 7 are mid-field and far-field respectively, with the projectile incident from right (The incident direction in Fig. 8 and Fig. 9 is the same). The damaged PBXN-5 shows more microcracks than undamaged samples. The mid-field and far-field regions show even more particle fracture than near-field region. A larger crack is present in mid-field region, showing coalescence of microcracks. Some transgranular cracks can be clearly seen in the micrographs.

Fig. 8 and Fig. 9 are images of near field and far field of damaged Composition B impacted under the same condition. Though some transgranular microcracks are also present in RDX particles, the number of microcracks and fractured explosive particles is much lower than damaged PBXN-5 samples. It is worthwhile to note that the substantial preferred orientation of the microcracks and the coalesced crack in mid-field and far-field is in the vertical direction for both PBXN-5 and Composition B samples. Fig. 10 is a fractograph of Composition B, demonstrating that intergranular fractures are the main fracture mode for Composition B. Some extruding RDX particels and some pits due to the pulling out of RDX particles can be clearly seen in the picture.

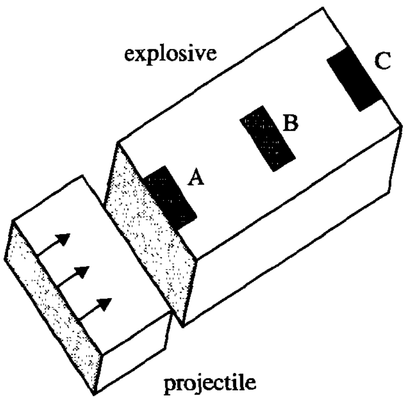

Fig.2 Schematic of view fields

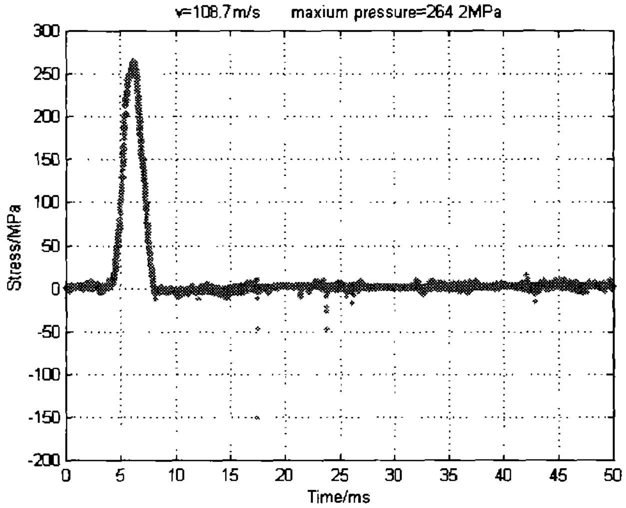

Fig.3 A typical stress history of impact loading

Few visible cracks can be observed in damaged PBXN-5 impacted by a steel projectile at a speed of 109 m/s. However several visible though cracks vertical to incident direction are present in damaged Composition B impacted under the same condition, and some large fragmentations on the opposite side of impact plane are produced. The results show that PBXN-5 possesses better resistance to impact loading, while Composition B is more brittle than PBXN-5. The composition difference between the two explosives may be the main reason for the results. Both RDX and TNT crystals in Composition B are brittle. Though the viscoelastic binder content in PBXN-5 is relatively low, only about 5 percent, it still noticebly enhances the resistance of the whole material to mechanical loading. Damage and failure of inhomogeneous materials under dynamic loading are related to both stress field and initial damage state and anisotropic characteristics of the materials. Our experiment provides a method and tool to analyze these phenomena. Some useful results may be obtained if further analysis and statistics can be done for these micrographs. These work is currently under way in our laboratory.

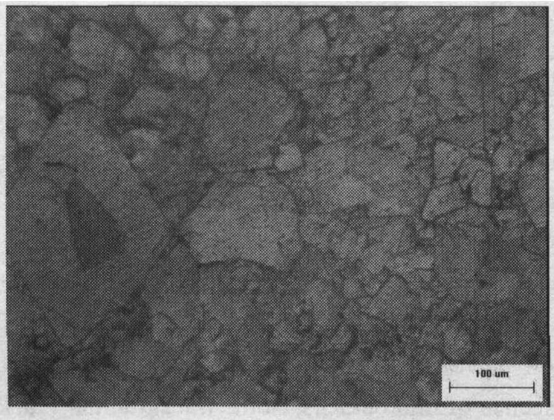

Fig.4 Plan view of undamaged PBXN-5 samples

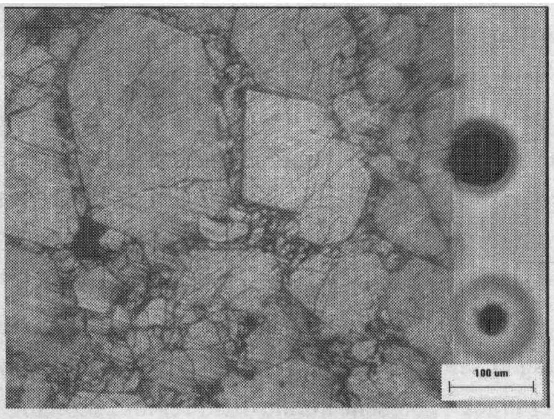

Fig.5 Near-field region, damaged PBXN-5

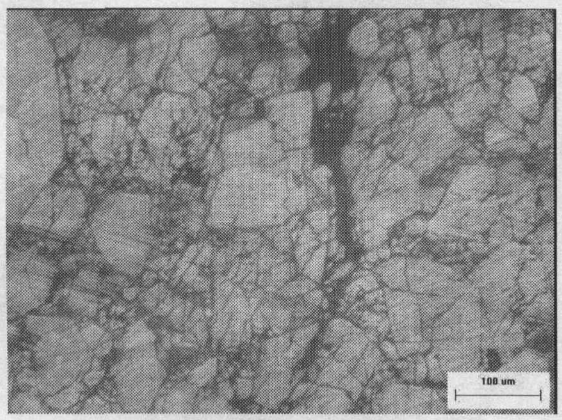

Fig.6 Mid-field region, damaged PBXN-5

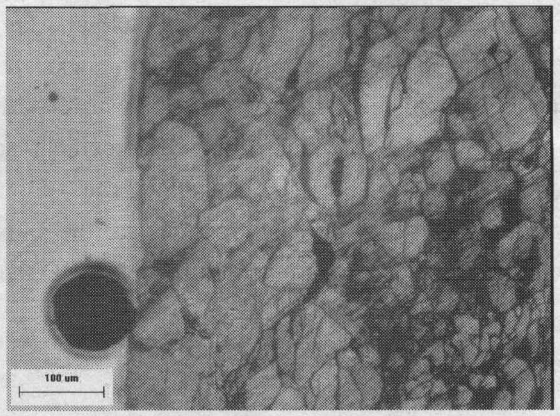

Fig.7 Far-field region, damaged PBXN-5

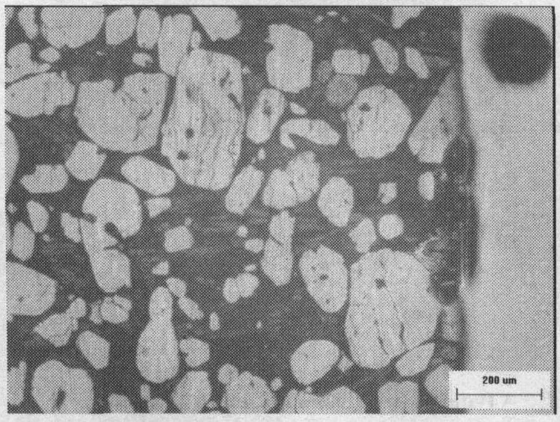

Fig.8 Near-field region, damaged Composition B

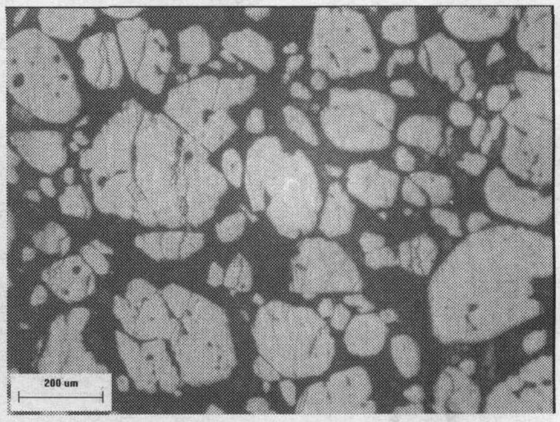

Fig.9 Far-field region, damaged Composition B

Table 1 shows the density variation before and after impact under different impact conditions. Due to the formation of extensive microcracks, the densities in damaged samples are reduced. The higher the impact stress is, the more the density reduces. When PBXN-5 samples are impacted by aluminum projectiles at speeds of 60.4, 125.4, 147.8, 191.4 and 194.1 m/s, the densities decrease by 0.214%, 0.273%, 0.525%, 1.082% and 1.114% respectively. When the samples are impacted by a steel projectile at a speed of 109 m/s, the densities of PBXN-5 and Composition B decrease by 1.82% and 0.42% respectively. Table 2 lists the ultrasonic attenuation coefficients of undamaged and damaged samples. It is also shown that higher impact velocities and shock stress cause more severe damage and larger ultrasonic attenuation. The attenuation coefficient of undamaged PBXN-5 is 2.60 dB/mm. While the attenuation coefficients of the damaged samples impacted by aluminum projectiles at speeds of 60.4, 125.4, 147.8 and 191.4 m/s increase to 2.85, 3.55, 4.67 and 4.72 dB/mm, showing an increase of 9.6%, 36.5%, 79.6% and 81.5% respectively. The results demonstrate that the variation of attenuation coefficient is much larger than the density for impact damage. The acoustic attenuation coefficient seems to a more sensitive variable than density

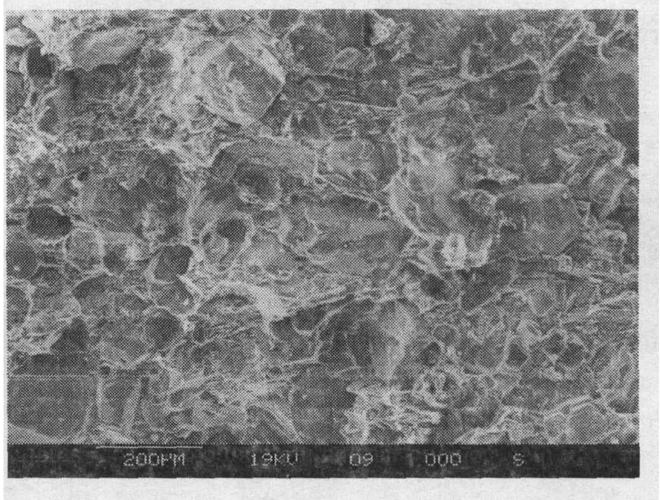

Fig.10 A typical fractograph of damaged and fractured Compositon B

Table 1 Densities of undamaged and damaged explosives

Materials	Projectile velocity/m.s^{-1}, peak pressure/MPa					
	60.4/56.3	125.4/113.3	147.8/--	191.4/212.5	194.1/--	109/*
PBXN-5	-0.214%	-0.273%	-0.525%	-1.082%	-1.114%	-1.82% (264MPa)
Comp B	--	--	--	--	--	-0.42% (283MPa)

*steel projectile, the rest are aluminum projectiles

Table 2 Attenuation coefficients of undamaged and damaged explosives

Acoustic properties	Undamaged	Projectile velocities/m.s^{-1}, peak pressure/MPa			
		60.4/56.3	125.4/113.3	147.8/--	191.4/212.5
Attenuation /dB.mm^{-1}	2.60	2.85	3.55	4.67	4.72

4 Conclusions

The long-pulse low-velocity gas gun used in our experiment proves to be an efficient loading apparatus in the study of dynamic damage and mechanical properties of explosive materials. Both PBXN-5 and Composition B exhibit damage characteristics of brittle materials. Impact induces a large number of microcracks, which causes the density to decrease and ultrasonic attenuation to increase. Higher projectile velocity and higher impact stress cause a larger degree of damage, a lower density and a larger attenuation coefficient. Composition B appears to be more brittle than PBXN-5. The composition difference between them may account for that. A few percent of binder in PBXN-5 can noticeably enhance the resistance of the whole material to impact loading. It is reasonable to speculate that a moderate increase of binder content may remarkably improve the mechanical properties of PBX materials, and may decrease the sensitivity of the explosives at the same time. This will not cause a noticeable loss of explosive energy.

The impact stress generated in our experiment is not high enough to induce chemical reaction in damaged explosives. To characterize the microstructure of explosives with local impact-induced chemical reaction, larger projectile velocities or a gas gap is planed to be used for further study. This may deepen our understanding of the formation mechanisms of hot spots under impact loading.

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