Deformation, fracture and mechanical properties of PBX under dynamic loading by using digital speckle correlation method

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Abstract: Brazilian test, semi-circular bend (SCB) test and compression experiments under dynamic loading were performed on a polymer bonded explosive (PBX) simulant by using a split Hopkinson pressure bar (SHPB). A high-speed photography was used to record the dynamic deformation and fracture process of the samples during impact. Based on the digital speckle correlation method (DSCM), the displacement and strain fields on the sample surface were obtained at macro-scale, revealing the deformation and fracture mechanisms of the specimen under dynamic loading. In addition, an optical microscope combined with a high-speed camera was used to record the dynamic deformation process of a local region near the preset crack in a SCB simulation sample. The strain field was computed by the DSCM technique at micro-scale, demonstrating the microscopic damage evolution and predicting possible failure growth of microcracks in the SCB specimen. Moreover, based on Mohr-Coulomb criterion, the ultimate failure parameters under dynamic uniaxial loading can be obtained. The experimental results are in agreement with theoretical analysis, demonstrating that the DSCM technique is effective to study the dynamic behavior of PBX materials.

Introduction

Polymer bonded explosives (PBXs) are particle-filled composite in which highly brittle crystalline explosives (90-95% by weight) are distributed in a soft polymer binder. The increasing use of PBX requires a greater understanding of these solid energetic materials. Characterizing the materials response to mechanical stimuli, especially at high strain rate, is important to develop a fundamental understanding of sensitivity and ignition. The split Hopkinson pressure bar (SHPB) is a common testing device used to establish the stress-strain relationship for materials at strain rates of approximately $10^2 s^{-1} \sim 10^4 s^{-1}$. In the Cavendish Lab, the quasi-static Brazilian test was widely used to study PBX and its simulation materials, usually in conjunction with deformation field measurement techniques [1-5]. Dynamic deformation field measurement is a hot topic in optical method research, which can be realized by digital processing of the images involving a random pattern of speckles on the sample surface, and a high-speed camera is used. In recent years, many valuable SHPB studies of PBX materials using both the DSCM technique and a high-speed camera have been reported [6-8].

There might be clear advantages to measuring deformation fields of sample during high-strain-rate loading, including the ability to predict the deformation and fracture modes and understand material failure mechanisms. In this work, experimental studies were done on investigation of the dynamic deformation and fracture of energetic materials. An inert simulation material of PBX was loaded in SHPB, and a high-speed camera (Photron Fastcam SA1.1) was used to record the fracture initiation and propagation process as well as the fragmentation of specimen body. Displacement and stain fields on the specimen surface were computed by using the DSCM technique at macro-scale. It's known that the knowledge of the non-uniform and localized strain field in heterogeneous materials is very useful for the investigation of the microscopic deformation and damage mechanisms governing the macroscopic mechanical behavior of such materials. In this work, we utilize the DSCM to study the microscopic damage and fracture behavior of a semi-circular PBX sample under dynamic compression by using a high speed camera combined with an optical microscope. The area of interest in specimen surface was observed by the optical microscope (QUESTAR Telescope) with dynamic loading steps, and the images recorded by the high-speed camera were used to extract the strain field by the DSCM technique at micro-scale, with the aim of investigating the damage evolution in the localized region of the specimen and predicting possible failure growth.

Experiments

Brazilian test

The Brazilian test is a biaxial method for estimating the tensile failure stress of a material without the inconvenience of uniaxial dumbbell testing. By applying a compressive load diametrically to a cylindrical sample, a tensile failure may be generated in the center of the sample just perpendicular to the load axis. Simple elasticity theory applied to plane anvils predicts that the tensile stress at the center is a maximum given by

$$\sigma = \frac{2p}{\pi D \delta} \tag{1}$$

where D is the sample diameter and δ is the sample thickness. If the full elastic expressions are evaluated over the disc whole field, it is found that the tensile stress along the load axis remains non-uniform near the center of disc, making the test invalid.

The modified Brazilian test configuration is shown in Fig. 1. The modification is that two parallel planes of equal width are introduced to the Brazilian disc specimen in order to lower the shear stress near to the anvil contact points. According to the analysis, when the load angle $2\alpha > 19.5°$, the crack is to be initiated at the center of the disc and will propagate along the load axis [9]. By applying a compressive load diametrically to a cylindrical sample, a tensile stress and failure may be generated in the center of the disc. In this work, the load angle is $19.5° < 2\alpha < 30°$, and the flattened setup facilitates loading the specimen.

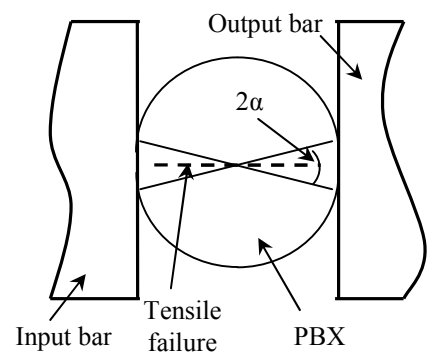

Fig. 1. Geometry of Brazilian test.

Semi-circular bend (SCB) test

Dynamic fracture plays a vital role in engineering applications. Accurate measurements of dynamic fracture parameters are prerequisite for understanding mechanism of fracture and also useful for engineering applications. For brittle materials such as PBX, one can't imply the standard method of fracture measurement developed for metals. Special sample geometries have been adopted for fracture toughness measurements. Chong et al [10, 11] used the semi-circular bend (SCB) specimen for rocks. This sample geometry is advantageous for convenient

sample preparation, thus used here for dynamic deformation and fracture measurement of PBX. The geometry of the SCB specimen is shown in Fig. 2. Its diameter is *D* and thickness is *B*, the depth of the preset notch is *a*, and the span of the supporting base pins is 2S. In our experiments, a SCB specimen was machined from a disc sample with a size of 20mm in diameter and 10mm in thickness, and an edge pre-notch with 1mm length and 0.2mm width was fabricated in the specimen perpendicular to the load direction. The strain field can be obtained by using the DSCM technique with the aim of investigating the dynamic failure mechanism of a SCB specimen at macro-scale. In addition, in order to study the microscopic deformation behavior of a SCB specimen under dynamic compression, the strain field of an area of interest (labeled area 0) was obtained by DSCM technique at micro-scale.

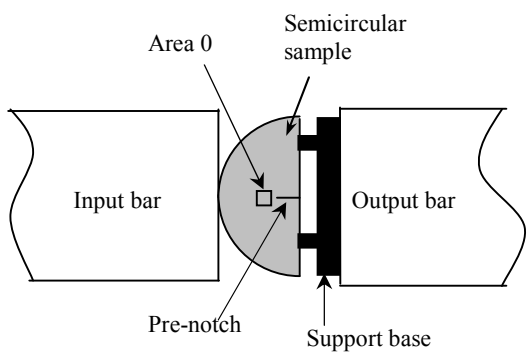

Fig. 2. Geometry of semi-circular bend test.

Deformation measurement by the DSCM

It is worth noting that, in recent years, DSCM has become popular in the field of experimental mechanics. Due to the advantages of no contacting measurement, and wide measurement range etc., the DSCM technique is an important development direction of the real time measurement technology at present. This technique is based on a mathematical correlation matching algorithm of the digital images captured before and after a deformation. Then a computer program correlates the gray levels of the sub-image in the deformed and undeformed images, and gives the horizontal and vertical displacement of each sub-image, and their strains. The basic principle of the DSCM has been discussed in refs. [12-15]. In this work, in order to investigate the deformation and failure mechanism of PBX simulation material at macro-scale, a random pattern of speckles on the sample surface was produced by spray painting. Information for displacement and strain field can be obtained by the DSCM technique. Moreover, the microstructural images of PBX were digitally processed by DSCM, giving the whole strain field measurement at micro-scale.

Results and discussion

Brazilian tests

The high-speed camera is used to observe the fracture initiation and propagation process of a flattened disc specimen. The inter-frame time is 50μs, and digital images with a resolution of 512×512 pixels. Each subdivision of the sample represents a 29×29 pixels sub-image, as used in digital correlation analysis. Fig. 3 shows the tensile strain field of the sample 1, which corresponds to the state just prior to total failure. The image clearly shows how the strain localizes along the center load axis of the disc sample. It can be seen that the maximum strain is concentrated in the disc center along the load axis, revealing the possible cracking route with increase of the external force. Fig. 4 shows the displacement vector plot presented on the post failure sample surface, with the input bar and output bar visible at both sides of the specimen. The arrows are scaled and can represent the relative displacement from the beginning of the experiment. The vector plot clearly shows the material at the upper and lower sides of the tensile failure route has moved vertically whilst material in the middle has been translated in the horizontal direction. In addition, just after the onset of failure, one separate crack can be observed. The results give a clear indication of the failure mechanism of the sample. The final image in this sequence, Fig. 5, shows a typical fracture route.

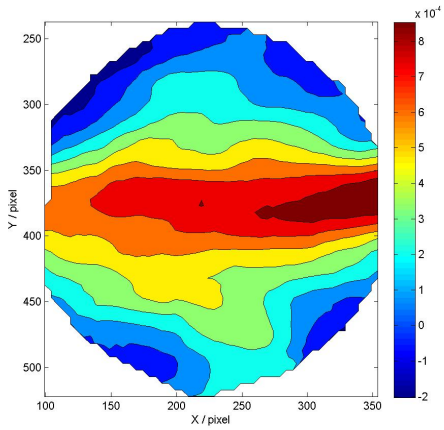

Fig. 3. Strain contour map of sample 1 prior to failure.

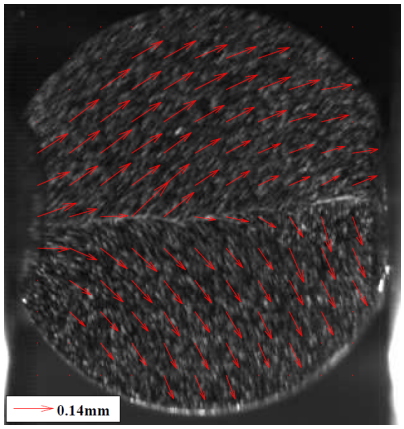

Fig. 4. Displacement vector field of sample 1.

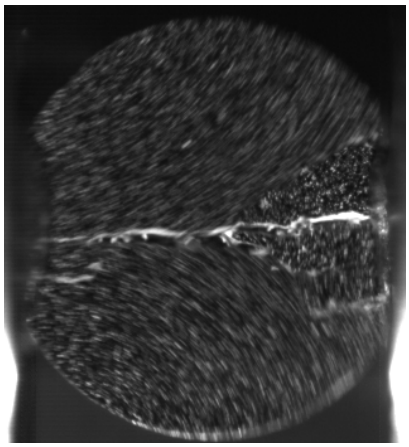

Fig. 5. Fracture monograph of sample 1.

With the increase of the framing rate, the size of view field decreased. In sample 2, measurement was focused on the central region of the disc sample. Inter-frame time is about 10μs, and the image resolution is 320×128 pixels.

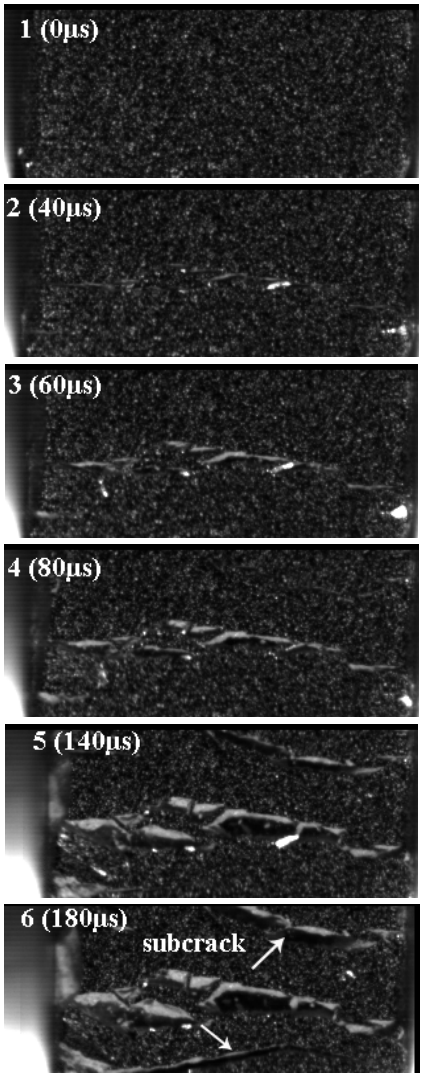

Fig. 6. SHPB impact sequence of sample 2 in Brazilian test.

The feature that distinguishes dynamic fracture from quasi-static behavior is the presence of the tensile stress waves which arise due to applied loads or stress release at the crack tip. When stress waves reflected from the specimen free boundaries

return to the crack tip, they will alter the crack tip stress state, and this can result in a change of crack speed or cause a crack branching if the intensity of the stress wave is sufficiently high. The impact velocity corresponding to sample 1 and sample 2 is 10.8m/s and 19.3m/s respectively. Therefore, in sample 2, the external load is higher and the effect of stress wave will be more significant. The initial specimen is shown in frame 1 of Fig. 6. After impact, the specimen deformed and many cracks were formed close the horizontal load axis and grew simultaneously (frame 2, 3 and 4), and cracks branching can be clearly seen in these frames. Cracks tend to branch out in order to decrease the energy of the system, and continued branching is the primary cause of fragmentation. The quasi-static failure will result in the propagation of a single crack, dividing a specimen into two parts. While under dynamic loading, the specimen body was eventually divided into many parts, see frame 6. It is also obvious that some of the sub-cracks can be seen, indicated by arrows in frame 6, which could be caused by the stress concentration in the local area between the flatten anvil and the arc surfaces of the disc sample. In addition, two different recording rates were used in dynamic Brazilian test. The recording speed 1.0×10^5 fps is sufficient to observe the fracture initiation and propagation process of the cracks.

Compression test

Uniaxial loading was applied on a sample with a size of 14.5×13.6×12.4mm by using a SHPB. A high-speed camera was used to observe the dynamic fracture process of the specimen. The inter-frame time is about 18.5μs, with a resolution of 320×256 pixels in each image. Like rock materials, the PBX simulant shows evident brittle and shear behavior under a compression action. In the SHPB test, the projectile impacts the input bar, then the block sample moved to right and produced deformation under the effect of stress wave. Generally, the maximum shear stress exists in two planes which are generally perpendicular and the angle between the shear failure planes and the load axis is about 45°. Strain field on the sample surface can be obtained by using the DSCM, as shown in Fig. 7. Fig. 7 (a) shows the extensive strain field of the block sample. It can be seen that the strain concentration mainly exists in the sample center near the input bar, with maximum strain magnitude of 0.06. It can also be seen that the shear strain bands are mainly localized in two planes which are perpendicular to the sample surface and symmetrical present along the load axis and the maximum strain magnitude is about 0.06, see Fig. 7 (b). Therefore, it is possible to observe the start of the crack in this region, and shear fracture will occur if the stress wave or the external force is sufficiently high.

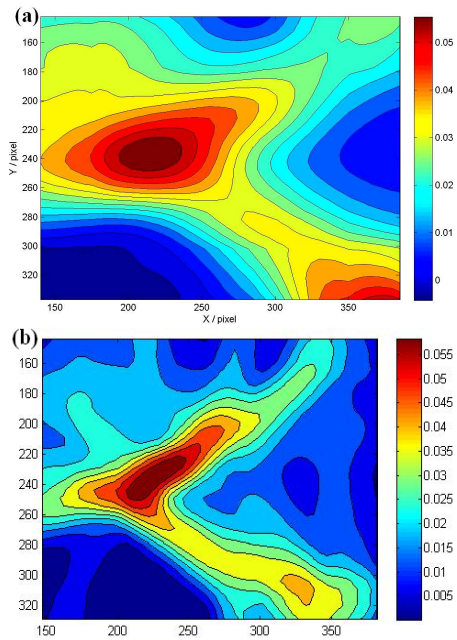

Fig. 7. Strain components distribution. (a) Extension strain. (b) Shear strain.

Fig. 8 illustrates a clear vector field of displacement for a block simulation sample. The arrows are scaled and indicate that the left materials are being driven right into the material in a wedge shape visible in the image. Fig. 9 shows the fracture morphology of the block sample, with clear shear displacement produced within the bottom of the block material. Such generation of shear deformation in explosive materials may be important in chemical reaction or detonation scenarios with sliding friction at a high strain rate.

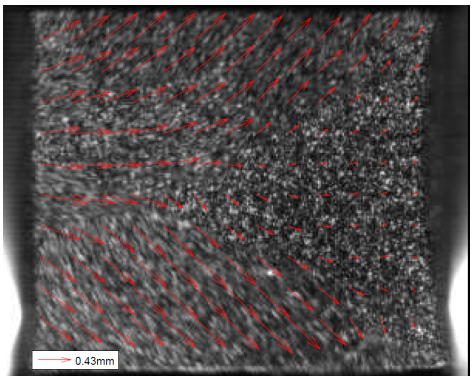

Fig. 8. Displacement vector field of sample prior to failure.

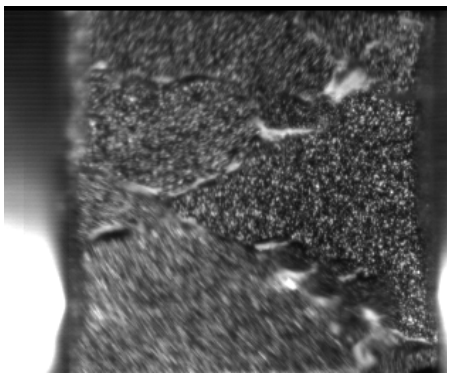
Fig. 9. Fracture morphology of a block sample.

Displacement and strain fields obtained have examined the observed fracture behavior and failure mechanism of block sample under dynamic uniaxial loading. Moreover, the Mohr-Coulomb criteria is one of the most widely used strength criteria in engineering application, and the validity and applicability of this criterion to material strength under dynamic loading has been supported by experiments study carried out by J Zhao [12]. It appears that the change in strength is due to the change of cohesion c, while the internal friction angle φ remains unchanged at different loading rates. The basic concepts of Mohr-Coulomb suggest that the shear strength of a material is made up of two parts: a constant cohesion and a friction varying with normal stress. The image of the post-failure block sample is given in Fig.9. Based on the Mohr-Coulomb criteria, the shear stress τ can be given on a failure plane in the form [16, 17]

$$\tau = \mu\sigma_n + c \tag{2}$$

where σ_n is the normal stress acting on failure plane and c is the cohesion, μ is the friction coefficient and can be calculated as $\mu = tan\varphi$. From the Mohr circle plot, the orientation of the plane of failure is given by [12]

$$\theta = \frac{\pi}{4} + \frac{\varphi}{2} \tag{3}$$

where θ is the angle made between the failure plane normal and the loading axis, φ is the internal friction angle of the material. In Fig. 9 the value θ is approximately 61°, then the friction angle φ can be calculated and the value is about 32°. Given the ultimate compressive engineering stress σ=9.0 MPa, the cohesion and dynamic tensile strength can be calculated as 2.88 MPa and 3.19 MPa, respectively. The mechanical parameters of materials under dynamic loading can be approximately described by the Mohr-Coulomb criterion, which is useful to understand the dynamic failure behavior and mechanisms of these materials.

Semi-circular bend (SCB) tests

Fig. 10 shows the high-speed sequence obtained for one of the experiments on a PBX simulation sample. The inter-frame and exposure time were both 10μs. The speckle quiver plot is presented in the SCB specimen surface, with both the input bar and output bar visible in each frame. The first correlation, between 0μs and 20μs, is not shown as only negligible displacements were measured. The arrows in the figures are scaled and represent the relative degree of displacement from the beginning of the experiment in each frame. In particular, at 50μs the materials moved to the upward and downward approximately perpendicular to the central load axis, and the maximum displacement magnitude is about 0.2mm, as shown in Fig. 10 (c). The plots also show that the SCB specimen experienced split fracture under dynamic compressive loading.

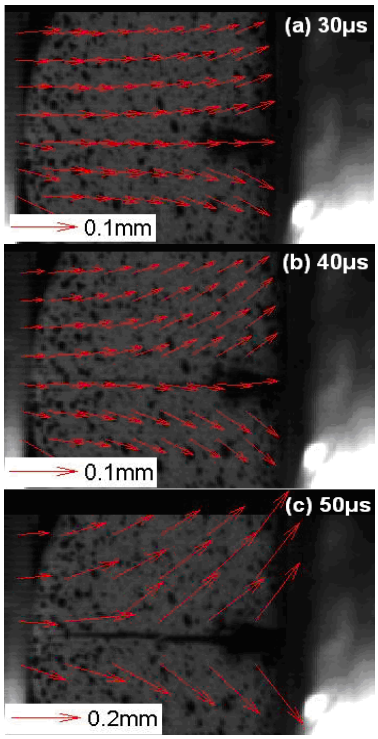

Fig. 10. Sequence of dynamic images of a SCB specimen deformation. Scaled displacement vectors are shown.

In order to further study the micromechanical behavior of PBX under dynamic compression, the present paper focuses on the localized strain field analysis by using the DSCM at the micro-scale. It consisted of a Photron Fastcam SA1.1 high-speed digital camera and an optical QUESTAR telescope for capturing microscopic speckle images. Two highly intensity lamps exposing the simulant specimen surface and the light beams are gathered on the specimen by using a pair of convex lens. The framing rate is 9000fps and the resolution of images is 896×752 pixels. Fig. 11 shows one microstructure image of the SCB specimen, which corresponds to area 0 in Fig. 2. A two-dimensional microscopic deformation field was measured on the microstructure images using the DSCM technique. Figs. 12 (a) and (b) show the two-dimensional extensive strain fields in the area I near the notch before the SCB specimen failure. It can be seen that the extensive strain field is not uniform. In Fig. 12 (a), many local areas show a significant strain concentration which may be caused by the original damage. The strain magnitude is small, such as the local areas A, B and C showing an obvious strain concentration. Comparing this to Fig. 12 (b), the strain magnitude of local area B and C has declined to an average, and a new local strain concentration area appears, such as the area E in front of area A ahead of the prefabricated notch, which may be caused by the damage exists in area A. More importantly, the results show that the extensive strain concentration is in the line with the preset crack, indicating that the possible fracture path will be along the pre-crack orientation.

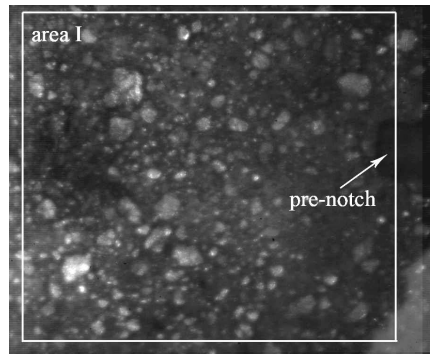

Fig. 11. Microstructure of a SCB sample.

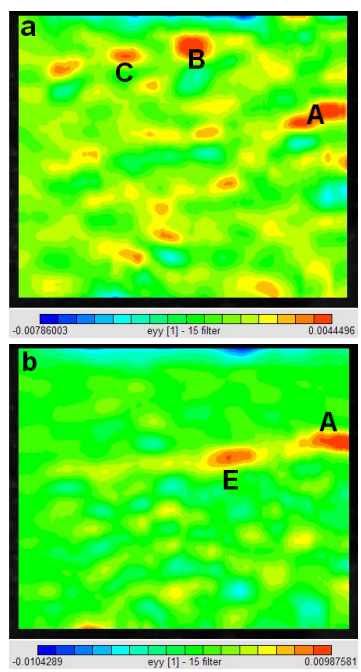

Fig. 12. Tensile strain field distribution of a SCB sample at two loading states.

Conclusions

We adopt a SHPB testing technique with the flattened Brazilian test, the uniaxial loading test and the semi-circular bend (SCB) test to study the dynamic deformation and fracture behavior of a PBX simulant. A high-speed camera was used to observe the deformation and fracture process of specimens. Based on the DSCM technique, the displacement and strain field measurement on the sample surface were obtained at macro-scale. The fracture models and failure mechanisms under different loading conditions were analyzed. Moreover, based on Mohr-Coulomb criteria, the friction angle, the dynamic cohesion and tensile strength magnitude were obtained, providing good explanations for the observed fracture behavior of PBX simulants. In addition, an optical microscope combined with the high-speed camera was used to observe the local region around the notch preset in a SCB specimen. The heterogeneous strain field was computed by the DSCM technique at micro-scale, demonstrating the microscopic damage evolution process and predicting possible failure path in the SCB specimen. The results show that the DSCM is effective to study the dynamic deformation and fracture behavior of explosive materials, in conjunction with a high-speed camera.

Acknowledgements

The authors acknowledge the financial support from the National Natural Science Foundation of China under contract number 10832003, the National Basic Research Program of China under contract number 613830202, and the Program for New Century Excellent Talents (NCET-06-0159). The authors also thank prof. Nie Fude from Institute of Chemical Materials, Chinese Physical Academy for providing PBX simulation materials.

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