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STUDY ON DYNAMIC FRACTURE AND MECHANICAL PROPERTIES OF A PBX SIMULANT BY USING DIC AND SHPB METHOD*

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Abstract. The deformation and fracture of a PBX simulant were studied in this work. A pre-cracked semi-circular bending sample was loaded using a SHPB. The failure process of the sample was recorded in situ using a high speed camera. Based on the recorded images corresponding to the loading steps, the displacement and strain fields were determined using digital image correlation method. The crack opening displacement was determined. The correlation coefficient distribution was used to predict the initiation and propagation of the crack initiated from the tip of the pre-crack. In addition, the dynamic fracture toughness of the specimen was measured. The K_{IC} values were approximately 1.39 ± 0.02, 1.51 ± 0.01 and 1.87 ± 0.03 MPa·m$^{1/2}$ corresponding to strain rates about 382 ± 13, 455 ± 8 and 621 ± 23 s^{-1}, respectively. The fracture toughness results show strong strain rate dependence.

Keywords: PBX simulant, digital image correlation, semicircular bending test, dynamic fracture toughness, SHPB
PACS: 46.50.+a, 42.30.Ms.

INTRODUCTION

The initiation and propagation of cracks are the dominant mechanical failure mechanism of high explosives, and the crack could affect both the safety and detonation performance of weapons and munitions systems. Therefore, safety concerns and performance of explosives have motivated many experimental researches [1-3]. Fracture mechanics parameters, such as fracture toughness characterize a material's resistance to crack propagation. The measurement of the K_{IC} requires knowledge of the specimen's geometry and a pre-crack fabricated within the material. Metallic materials traditionally used pre-notch methods for growing a natural crack starter, and the three-points bending test was used to measure the fracture toughness. Afterward, the three-points bending test was also used to determine the fracture toughness of explosives with the pre-crack fabricated using a razor blade [4]. However, for explosives, these polymer matrix composites are brittle materials, with low strength. It is difficult to machine a three-points bending sample because of strict limitation of the specimen size. As an alternative, the semi-circular bending sample is easy to obtain by machining the original disc shaped sample; therefore, we chose the semi-circular bending test in this study.

Recently, the digital image correlation (DIC) method is widely used in experimental mechanics as a practical and effective tool for full deformation field measurement [5]. This technique is easy to manipulate and can provide satisfactory resolution of displacement and strain fields. Many studies were performed in the literature to evaluate the deformation behavior and fracture mechanism of PBX using DIC at macro and micro scale. Rae et al.

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first [6] used DIC to investigate the effect of thermal aging on a UK PBX. And in Rae et al. [6] the method was described in detail including an extended discussion on error analysis. Specially, with the aim at studying the microscopic damage initiation and propagation, the strain fields distribution were measured and the failure mechanisms of PBX were studied using DIC at micro-scale combined with an optical microscope or an SEM imaging system [7-8].

In this work, semi-circular shaped sample was dynamically compacted using a split Hopkinson pressure bar (SHPB), and a high speed camera was used to in situ monitor the fracture process of the specimen. The objective of our work is to quantify the process of crack initiation and propagation in PBX. Based on the DIC, the dynamic deformation and fracture behavior of PBX could be analyzed. In addition, the dynamic fracture toughness of PBX was measured.

EXPERIMENTS

A PBX simulation material was used in this study, which is comprised of high percent organic particles held together by fluoro-rubber. The sample was hot pressed in a steel mold. A disc shaped sample with diameter of 20 mm was obtained, then the disc was cut symmetrically into two semi-circular slices; therefore, semi-circular shaped specimen was obtained.

Usually, traditional uniaxial tensile test is inconvenience for brittle materials. Test should be done with compressive loading where tensile fracture is induced. Chong et al. [9] first proposed a bending test using a semi-circular shaped sample subjected to a three-points bending load. Fig. 1 shows the dynamic loading geometry of the semi-circular bending (SCB) test. In Fig. 1, the SCB sample was placed between the input and output bar. The initial pre-notch was fabricated along the line of symmetry at the specimen edge and oriented along the loading direction. A high speed camera was vertically placed to the sample surface. A series of digital images was recorded at a frame rate of 10^5 frames per second, with resolution of 258×400 pixels^2 in each image.

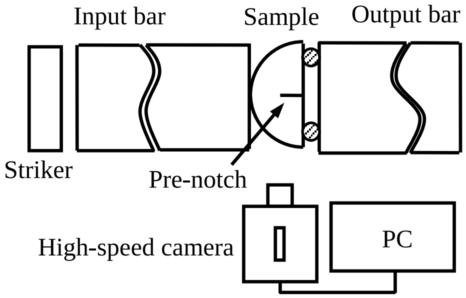


Figure 1. Geometry of the dynamic SCB test.

Considering the specimen geometry, tensile crack (model I) is induced in SCB specimen. Fracture toughness K_{IC} under mode I condition can be calculated from the stress intensity factor solutions, which is given by

$$K_{IC} = \frac{P_C\sqrt{\pi a}}{DB}Y_K \tag{1}$$

where P_C is the failure load, D is the diameter of SCB sample and B is the thickness. Y_K is the dimensionless stress intensity factor as a function of dimensionless crack length, a/D. Y_K is approximated by a third order polynomial as follows

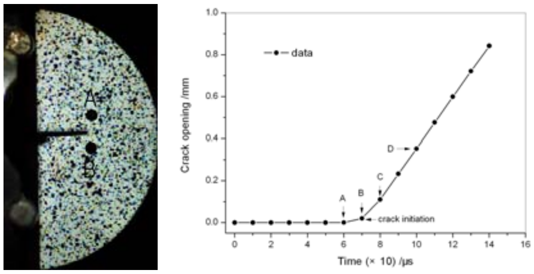
$$Y_K = 4.47 + 7.4\frac{a}{D} - 106(\frac{a}{D})^2 + 433.3(\frac{a}{D})^3 \tag{2}$$

In Eq. 1, it is obvious that the fracture toughness K_{IC} is directly proportional to the critical failure load P_C. So in this work in order to measure the fracture toughness, the key point is to precisely determine the critical failure load.

RESULTS AND DISCUSSION

Macroscopic crack opening determination

In DIC analysis, the full surface of the SCB sample was chosen for the displacement and strain fields measurement. The subset size is 29 × 29 pixels^2, and the step size is 4 pixels. Determination of the crack opening displacement was carried out. As seen in Fig. 2(a), we picked up two points (labeled as ‘A’ and ‘B’) in the front of the crack tip. With increasing external force, the SCB sample deformed continuously. Reaching the peak load level, the crack initiates; therefore, the distance between these two key points can be determined by $\delta = \delta_+ - \delta_-$, which represents the opening displacement of the crack. Fig. 2(b) shows the variation of crack opening displacement as a function of the loading time. An obvious feature of such a variation is that crack opening exhibits a sharp transition during the process of the deformation. It is seen that during the early stage of the deformation, crack opening $\delta = 0$ and changes very little. After a particular moment of time, δ monotonically increases with increasing of the loading time until the last stage of the deformation.



(a) (b)

Figure 2. Determination of the crack opening. (a) DIC analysis area; (b) Relationship between crack opening displacement and loading time.

Crack initiation and propagation measurement

One of the major challenges in studying fracture and failure of explosives and their mock materials is that it is difficult to actually see the cracks before they grow large enough. Even though the results shown in Fig. 2(b) clearly suggest the initiation and presence of macroscopic crack in SCB specimen, we are still unable to point the exact moment of crack initiation and the exact location of the macroscopic crack tip. A technique has been developed recently to quantitatively describe the initiation and propagation of cracks in explosive simulation material [8]. This technique is based on some quantitative information that generated during the DIC calculations of the deformation field. In the DIC, the correlation coefficient c is a function of the grey values of the two digital images before and after a deformation. When the distortion of the small region is such a feature that two small images match each other, the c reaches a minimum. However, when damage or cracks develop in the small region during deformation, the correlation coefficient may not be able to attain minimum, the value of the coefficient c becomes much bigger than other regions where no damage or cracks are present. Based on this, the correlation coefficient was used to quantify the location and extent of cracks in SCB specimen.

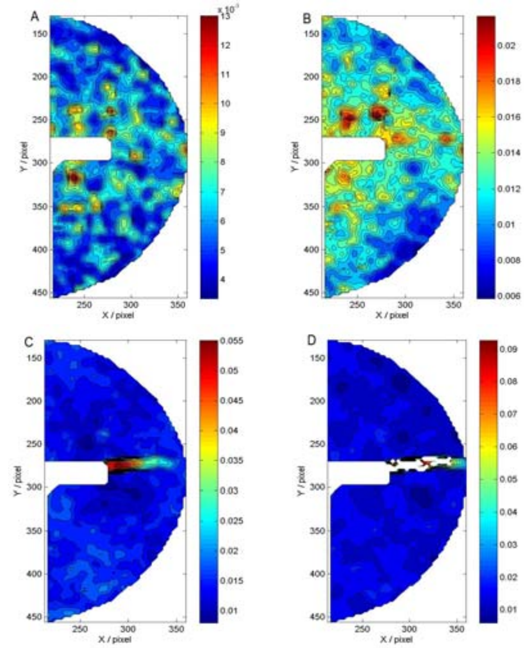


Figure 3. Selected contour plots of the correlation coefficient of SCB specimen.

Fig. 3 shows the contour plots of the normalized correlation coefficient c field in SCB specimen at four loading states. The moments, including A, B, C, and D, were labeled in Fig. 2(b). Note that the correlation coefficient c is a scalar field and will evolve during the deformation. The normalized correlation coefficient varies between 0 and 1, with 0 indicating good matching between initial figure and deformed figure. In Fig. 3, at the moment A, it is seen that the coefficient c is very small without crack initiating. In the following moment, it is noticed that the coefficient c increases. As we have discussed before, when the c becomes bigger than a critical parameter, degradation of the speckle image is indicated, which is caused by the damage and cracking of the material underneath of the image. Particularly, in the moment C, the maximum magnitude of the c is about 0.055, the crack initiated in the front of the tip of the pre-notch. The light red lines represent the boundaries of regions occupied by the macroscopic crack. In the last moment, the maximum *c* value is approximately 0.1. Because of seriously degradation of the speckle image, e.g. speckle spots were eroded which was caused by the cracking; therefore, the light white region ahead of the pre-notch tip represents the growth route of the crack. Moreover, it is seen that the macroscopic crack almost penetrates the specimen along the pre-notch direction.

Fracture toughness determination

In SHPB system, the incident, reflected and transmitted wave signals were recorded using the strain gauges; therefore, the impact force on the specimen can be determined. Finally, based on the Eq. (1) and Eq. (2), the dynamic fracture toughness of the SCB specimen was calculated. The results are shown in Fig. 4 as triangular symbols, together with the fitting curve of the data. It is obvious that the fracture toughness increases with increasing strain rate. The K_{IC} values are approximately 1.39 ± 0.02, 1.51 ± 0.01 and 1.87 ± 0.03 MPa·m$^{1/2}$ corresponding to strain rates about 382 ± 13, 455 ± 8 and 621 ± 23 s^{-1}, respectively. The results show that the fracture toughness exhibits strong strain rate dependence.

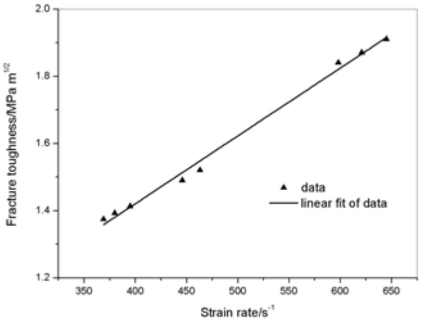


Figure 4. Variation of dynamic fracture toughness K_{IC} as a function of strain rates.

CONCLUSIONS

The method combining a SHPB with high-speed DIC technique was successfully used to study the dynamic fracture behavior of PBX simulant. The displacement and strain fields were measured, the crack opening displacement were determined, and the initiation and propagation of the crack were quantitatively studied using the DIC. The results indicate the fracture mechanisms of the specimen, showing that the specimen fractured under extension stress with a split failure. In addition, the dynamic fracture toughness of the specimen was measured. The magnitude of K_{IC} increases with increasing strain rate, exhibiting strong strain rate dependence.

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