Experimental Determination of the Dynamic Initiation Fracture Toughness of Composite Modified Double base Propellant

W.Q. Wang*, X. Chen, J. Zheng, J.S. Xu, C.X. Sun
School of Mechanical Engineering
Nanjing University of Science and Technology
Nanjing, Jiangsu, China
*Corresponding author

Abstract—**This paper presents a detailed experimental procedure for determining the dynamic initiation fracture toughness of Composite Modified Double-Base (CMDB) propellant under dynamic loading. The Cracked Straight Through Flatten Brazilian Disc (CSTFBD) specimens were conducted using the split Hopkinson pressure bar（SHPB）system under high loading rates. Experimental setup, data acquisition and interpretation were described in details. The strain gauge was adopted to monitor the time-to-fracture accurately. We interpreted the detailed procedure of getting the time-to-fracture, as well as confirmed all the propellant specimens were in a state of dynamic force equilibrium. Experimental results show that the CMDB fracture initiation toughness depended on loading rate. The pattern of destroyed sample indicated the solid propellant material was evident brittle fracture under dynamic loads.**

Keywords-composite modified double base propellant; initiation fracture toughness; loading rate

I. INTRODUCTION

Dynamic fracture toughness characterizes the ability of the material to resist destruction under impact loads. In many cases, Solid Rocket Motor (SRM) explosion accidents are directly related to the dynamic fracture of the propellant structure. Fully understanding the dynamic fracture characteristics of the propellant material keeps great guiding significance for the SRM design. In recent years, people have already paid great attentions to research the dynamic fracture properties of solid propellant under impact loading. M.Nait Abdelaziz[1,2] utilized the 'J-integral' theory to research the fracture toughness of the solid propellant under three kinds of high loading rate in SHPB system. He applied a modified equation that took into account the specimen compliance to analysis the loading rate sensitivity of the solid propellant under high loading rate. S.Y.Ho [3] used a modified SHPB to investigate the fracture properties and impact ignition sensitiveness of the solid propellant under dynamic loading, and the results showed the ignition sensitiveness was more pronounced during brittle fracture in the structure of the solid propellant. Fong C.W [4] applied linear elastic fracture mechanics to research the effect of AP particle size and orientation on the fracture toughness of solid propellant, and he found the dynamic fracture toughness was virtually independent of strain rate over the range from 3 to 90s-1. However, there have been few studies involved in the solid propellant dynamic fracture over a wider range loading rates so far.

SHPB is a kind of dynamic loading apparatus, which is a proven technique and has been applied widely in recent years. People have been taking advantage of this experimental technique to make significant progress in researching on the dynamic fracture properties of materials, such as metal, rock, polymer, etc. In this paper, we set out to investigate the relationship of the dynamic initiation fracture toughness of solid propellant and the loading rates with the SHPB technique under dynamic loading.

The scope of this paper is as follows. Firstly, Section 2 describes the experiment procedure to obtain data and the validation of SHPB test is verified. Section 3 gives the detailed discussions. Section 4 provides the conclusion of this paper.

II. EXPERIMENT

A. Materials

The solid propellant material in this study is provided by the manufacturer of North Industries Group Corporation in china. It is one kind of highly energetic composite materials. The CSTFBD schematic and picture were shown in Fig.1. In this paper, the solid CMDB propellant material was made into the CSTFBD specimen and conducted using a modified SHPB system. Moreover, all the specimens are placed into the thermostatic cabinet to eliminate the residual stress that located at the tip of the crack-tip by varying the temperature from 50°C to 20°C for 24 hours, respectively. Furthermore, for the purpose of minimizing the friction caused by the impact rigidly, the bar/specimen interface lubricated with the molybdenum grease. The geometric parameters for geometrically similar specimens are given in Table.1.

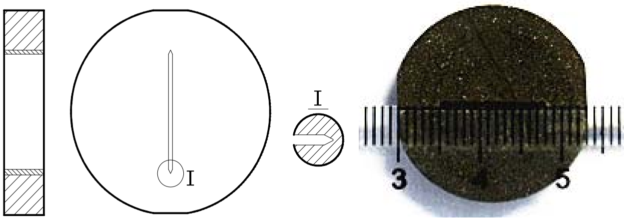

FIGURE I. THE SCHEMATIC AND PICTURE OF CSTFBD

TABLE I. GEOMETRIC PARAMETERS OF CSTFBD SPECIMENS

Diameter 2R /mm	Thickness B/mm	Crack length 2a /mm	Crack width b/mm	Load angle φ/°
25	8	14	0.75	20

B. *Split Hopkinson Pressure Bar (SHPB)*

Dynamic fracture test were conducted on a 14.5mm diameter modified SHPB system. A schematic of experiment setup was shown in Fig.2. The SHPB system consisted of a gas gun, a striker (0.4 m in length), an incident bar (1.4 m in length), a transmission bar (1.4 m in length), a momentum bar (0.3 m in length). The bars and striker were made from high strength high strength LC4 aluminum alloy (14 mm in diameter) having a nominal modulus of 74GPa and the Poisson's ratio was 0.3. A favorable location of the strain gauge was attached on the incident bar and transmission bars. The distance from the strain gauge to the bars/specimen interfaces was 700mm, respectively. Strain gauges connected to a dynamic strain meter through a Wheatstone bridge and a differential amplifier to record the voltage history, namely in purpose of recording the real-time strain signal value. Meanwhile, another two strain gauges were attached on the specimen to monitor the time-to-fracture. All of the raw data observed on the dynamic strain meter were processed after being digitally filtered using a low-pass filter with a frequency of 10MHz.

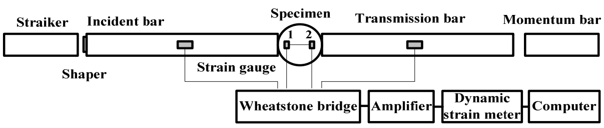

FIGURE II. THE SCHEMATIC OF THE SPLIT HOPKINSON PRESSURE BAR SYSTEM

C. *Pulse-shaper Technique*

The pulse-shaper technique in SHPB is especially important for investigating dynamic response of materials under dynamic loading [5]. Without proper pulse shaping, it is difficult to achieve dynamic stress equilibrium in such materials because the specimen may fail immediately from its end in contact with incident bar when it is impacted by the incident bar. What's more, the rigid-impact-contact caused by the bar/striker will bring about high frequency bit noise in the dynamic tests [6,7]. In this experiment, we found that a combined disc shaped pulse shaper made from soft materials (copper and rubber) can be utilized to minimize the high frequency bit noise to obtain ideal results. The combined shaper was placed in the incident bar/striker interface. A typical recorded result was given in Fig.3. Both the rough pulse and shaped pulse were shown, respectively. It can be seen from Fig.3 that with the pulse shaper technique, the rising front of the stress pulse is not steep and high frequency oscillating components disappear.

To ensure force balance on the CSTFBD specimen, we compare the time-varying testing signals on both ends of the specimen for typical dynamic CSTFBD test with pulse shaping in SHPB (Fig.4). It can be seen from Fig.4 that with the pulse shaper technique, the dynamic force balances and stress equilibrium in the CMDB propellant specimen during the dynamic test has been achieved.

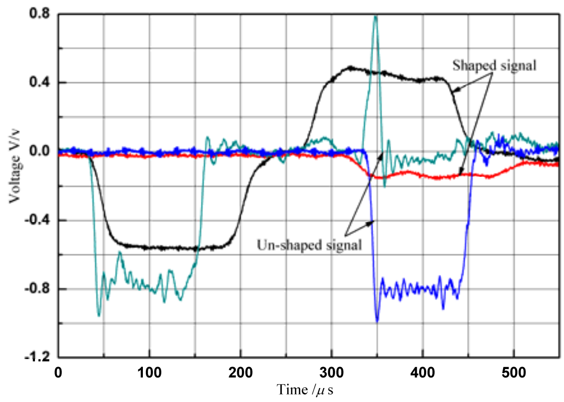

FIGURE III. RESULTS OF THE ROUGH WAVE AND SHAPED WAVE

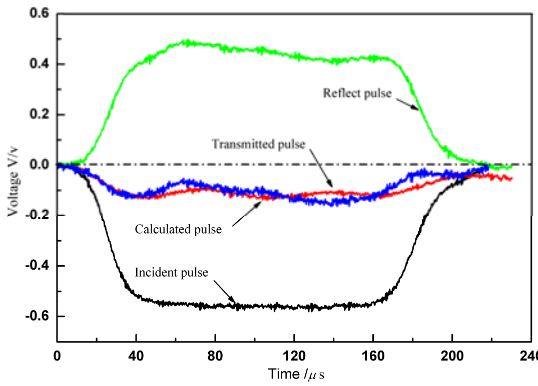

FIGURE IV. DYNAMIC FORCE BALANCE CHECK FOR DYNAMIC TEST

The load applied to the specimen is given below and is based on one-dimensional wave theory [8]:

$$P(t)=\frac{1}{2}(P_1+P_2) \quad P_1=EA(\varepsilon_I+\varepsilon_R), P_2=EA\varepsilon_T$$

Where E is the Young's modulus of the bar, A is the cross-sectional area of the bar, εI(t), εR(t), εT(t) are the strain signals at the bar-specimen interface.

D. *Fracture Time (tf) Determination*

The initiation time namely the time-to-fracture is essential to determine the dynamic initiation fracture toughness of the material [9,10]. It is quite difficult to monitor the initiation time accurately under dynamic condition. For the purpose of detecting the time-to-fracture accurately, two strain gauges were placed centro-symmetric in the direction of the pre-crack propagation direction. Fig.5 represented the typical results of the time-to-fracture. By comparing the two results detected by SG1and SG2 increased accuracy of fracture time determination can be ensured.

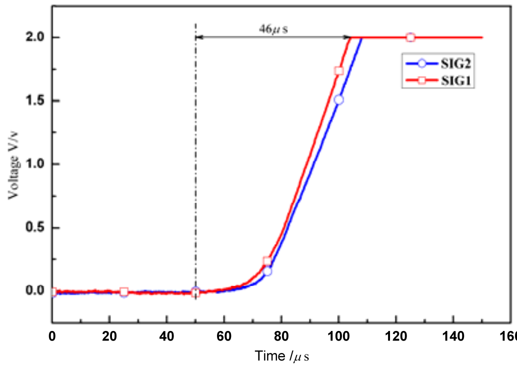

FIGURE V. RESULTS OF TWO STRAIN GAUGES

E. Dynamic Fracture Toughness Determination

Dynamic fracture toughness can be determined as the critical stress intensity factor value at the crack tip at the instant of crack initiation [11]. For mode-I dynamic fracture toughness can be determined by the following equation [12]:

$$K_I(t) = \frac{P(t)}{B\sqrt{R}} Y(2\beta, \alpha)$$

Where P (t) is the dynamic loading history, B is the thickness of the specimen, R is the radius of the specimen, Y is the mode-I fracture geometry factor which is determined by the geometry of CSTFBD specimen and it was shown in Fig.6.

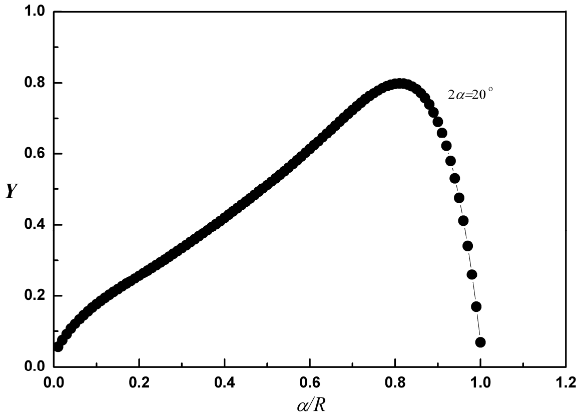

FIGURE VI. THE VALUE OF DIMENSIONLESS Y

III. RESULTS AND DISCUSSION

In order to systematically discuss the dynamic fracture characteristics of the solid propellant material, six results were selected. The results of the dynamic tests over a wider range of striking velocity are illustrated in Fig.7. It can be seen that all the initial peaks almost occur at the same time, i.e. was about 45.5us. What's more, the initiation time monitored by the contact measurement technique, i.e. the strain gauge and a designed electrical circuit technique, and the result was illustrated in Fig.5, it can be seen that the initial time measured by SG1 was 46us. It is clearly that the error is very small, which compared with the initial peaks in six group tests, just 0.5us. The tiny error can be understood considering the small delay caused by the adhesive used for attaching the strain gauge, which is reasonable and negligible under dynamic loads.

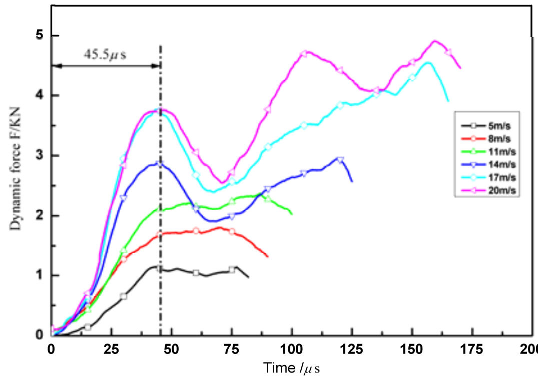

FIGURE VII. TYPICAL RESULTS AT SIX IMPACT VELOCITIES

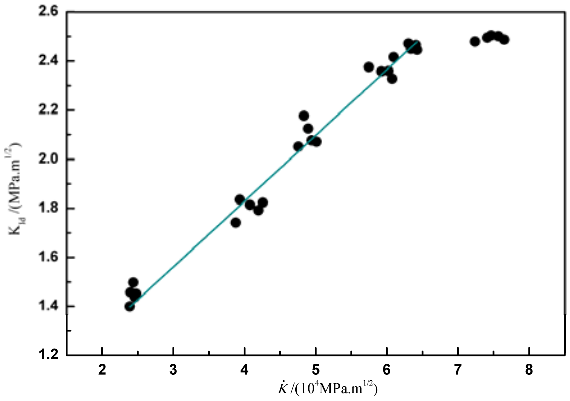

FIGURE VIII. DYNAMIC FRACTURE TOUGHNESS VERSUS LOADING RATES

Dynamic initiation fracture toughness normalized by the quasi-static theory was plotted as a function of applied loading rates, as shown in Fig.8. It can be seen that the initiation fracture toughness increased with loading rates ranging from 2.4×10^4MPa.m/s to 6.5×10^4MPa.m/s, which suggests that the propellant is a kind of loading rate sensitive material in dynamic loads. However, the results showed that the dynamic fracture initiation toughness not increased any more while the loading rate reached 7.2×10^4MPa.m/s, but tended to be a constant value. A reasonable assumption could be that the inherent details deformation and fracture morphology of particles within propellant matrix govern the process of fracturing at higher loading rates.

IV. CONCLUSIONS

A novel experiment method for determining the dynamic initiation toughness of CMDB propellant under dynamic loading was presented. This was achieved using a modified SHPB. The strain gauge was applied to monitor the time-to-fracture of the specimens with a quite accuracy, which suggests that this technique was reasonable and reliable to detect the initiation failure time of the solid propellant in dynamic tests. This technique is expected to be utilized in future and become increasingly popular with its practicability and economically.

Effect of loading rate on initiation fracture toughness had been investigated. The result indicates the propellant is a kind of loading rate sensitive material in dynamic loads, since the initiation fracture toughness increased with increasing loading rates ranging from2.4×10^4MPa.m/s to 6.5×10^4MPa.m/s. However, the results showed that the dynamic fracture initiation toughness not increased any more while the loading rate reached 7.2×10^4MPa.m/s, but tended to be a constant value.

REFERENCES

[1] Abdelaziz M N, Neviere R, Pluvinage G. Experimental method for JIC computation on fracture of solid propellants under dynamic loading conditions [J]. Engineering Fracture Mechanics, 1987, 28 (4): 425-434.

[2] Abdelaziz M N, Neviere R, Pluvinage G. Experimental investigation of fracture surface energy of a solid propellant under different loading rates [J]. Engineering fracture mechanics, 1988, 31(6): 1009-1026.

[3] Ho S Y, Fong C W. Correlation between fracture properties and dynamic mechanical relaxations in composite propellants [J]. Polymer, 1987, 28(5): 739-744.

[4] Chyuan S W. Dynamic analysis of solid propellant grains subjected to ignition pressurization loading [J]. Journal of sound and vibration, 2003, 268(3): 465-483.

[5] Dong S, Xia K, Huang S, et al. Rate dependence of the tensile and flexural strengths of glass–ceramic Macor[J]. Journal of Materials Science, 2011, 46(2): 394-399.

[6] Fengchun J, Ruitang L, Xiaoxin Z, et al. Evaluation of dynamic fracture toughness KId by Hopkinson pressure bar loaded instrumented Charpy impact test[J]. Engineering fracture mechanics, 2004, 71(3): 279-287.

[7] Xu Z J, Li Y L, Huang F L. Application of split Hopkinson tension bar technique to the study of dynamic fracture properties of materials [J]. Acta Mechanica Sinica, 2012, 28(2): 424-431.

[8] Lindholm U S. Some experiments with the split hopkinson pressure bar□[J]. Journal of the Mechanics and Physics of Solids, 1964, 12(5): 317-335.

[9] Bertram A, Kalthoff J F. Crack propagation toughness of rock for the range of low to very high crack speeds[J]. Key Engineering Materials, 2003, 251: 423-430.

[10] Parnas L, Bilir Ö G, Tezcan E. Strain gage methods for measurement of opening mode stress intensity factor[J]. Engineering fracture mechanics, 1996, 55(3): 485-492.

[11] McNamara D, Alveen P. Dynamic fracture of advanced ceramics under impact loading conditions using a miniaturized Kolsky bar[C]//ICF13. 2013.

[12] Wang Q Z, Jia X M, Kou S Q, et al. The flattened Brazilian disc specimen used for testing elastic modulus, tensile strength and fracture toughness of brittle rocks: analytical and numerical results [J]. International Journal of Rock Mechanics and Mining Sciences, 2004, 41(2): 245-253.