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Experimental Study on Boron–Potassium Nitrate Initiated by Shock

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This paper is concerned with the shock ignition of pyrotechnic-composition, boron–potassium nitrate ($B–KNO_3$) by means of a one-stage gas gun that is used as a shock-loading device. The pressure–time curves on the surface of a sample with different projectile velocities are measured by manganin gauges. Other Hugoniot parameters such as shock-wave velocity, particle velocity, and the approximate values of local sound velocity C_0 and coefficient λ related to its property for the $B–KNO_3$ samples are also determined. It is shown that the critical shock pressure of the sample with its chemical reaction is about 1.52 GPa with a 3.45-μs time delay.

I. Introduction

PYROTECHNIC compositions are usually ignited by means of heat, friction, and flame. However, in modern applications, high requirements on the accuracy of ignition delay and the safety and reliability of the composition are the major considerations in the design of pyrotechnic elements. At the same time, insensitive pyrotechnic compositions are developed in some applications, and ignitions by heat and flame are avoided by designing regulation. Therefore, shock initiations, which are used to evaluate the shock sensitivity of high explosives in the explosive field, are also involved in the study of pyrotechnics. Among the earlier research projects on the shock ignition of pyrotechnics was the work by Hardt and Martinson.[1] The method was used to induce foil vapor or explosion to drive the flying plate to impact the sample. The velocity threshold of shock ignition was the major parameter measured. Later work includes Lee and Schwarz[2]; they studied the response of titanium subhydride–potassium perchlorate $TiH–KClO_4$ (33/67) to the shock. The pressures on the impact surface were measured. Sheffield and Schwarz[3] reported their research work on the shock ignition process of $TiH_{0.65}–KClO_4$ that was induced by several means. Lombard et al.[4] gave the regularity of the effect of components, proportion, density, bulkhead thickness, and initiation manner on the performance of shock ignition. Sychev[5] observed the phenomenon of shock ignition in a liquid bubble active system. Hornig et al.[6] reported the results about the shock ignition of the mixture of Al and Fe_2O_3. Shock impact experiments of two kinds of gun propellant were completed by Weirick.[7,8] Aoki et al.[9] measured the bulkhead thickness of some pyrotechnics with a 50% ignition probability using an up-and-down method. Chen and Shen[10] and Chang et al.[11] reported, respectively, their research results on the shock ignition by the use of a bulkhead method.

The shock initiation mechanism of pyrotechnics is not clear because the ignition processes are more complex than those for high explosives. Investigations on Hugoniot parameters for pyrotechnics are rare in the literature. Accordingly, the present paper focuses on the experimental aspects to understand the mechanism of shock ignition of pyrotechnics. In the present work the one-stage gas gun is used and $B–KNO_3$ is the subject of investigation because the authors are using it for additional projects.

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II. Experiments

A. Experimental Setup

The one-stage gas gun at the Institute of Fluid Physics, China Academy of Engineering Physics, Chendu, Sichuan Province, was employed as a shock-loading device. The diagram of the setup is given in Fig. 1. The setup consists of the projectile, flying plate, brush-pins, target, and sample. The sample to be measured is fixed on the back of the aluminium target. F_4/203A manganin gauges with M-shapes and 0.11–0.22Ω are placed at the center of the interface of the sample and the target. Their use limit is in a range of 4 to 30 GPa. The flying plate is attached to the projectile to impact the target at a certain velocity.

When the projectile impacts the target, at the impact surface a shock wave is formed simultaneously in the flying plate and in the target. As the shock wave in the target arrives at the back surface contiguous to the sample, the manganin gauge receives an electrical signal that can present the history of shock pressure with time.

B. Sample and Target

In the experiment, $B–KNO_3$ (24/76) samples are processed in pellet form with a diameter of 40 mm and a thickness of 5 mm. Its density is about 1590 kg m^{-3}. The target made by aluminium has a diameter of 100 mm and a thickness of 3 mm, and the flying plate also made by aluminium has a diameter of 70 mm and a thickness of 18 mm.

The intimate contact of surfaces of the manganin gauge with the sample and the target is carefully assured to get real pressure value. The strength and flatness of the entire target is also carefully assured.

C. Techniques for Measurement

The diagrams of the system for measuring velocity and shock pressure for the ignition by shock are given in Figs. 2 and 3, respectively.

The measurement of the projectile velocity is realized through brush-pins (see Fig. 3). The intensity of shock formed

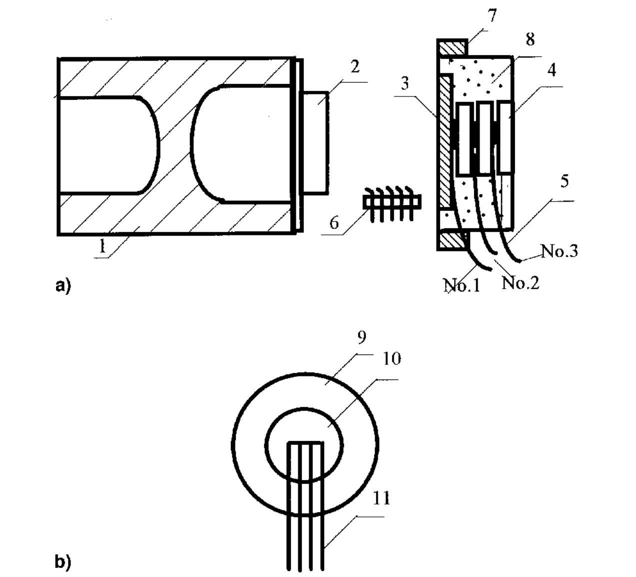

Fig. 1 a) Diagram of setup for samples and b) target and sample with manganin gauge. 1, projectile; 2, aluminium plate; 3, 9, aluminium target; 4, 10, samples; 5, 11, manganin gauges; 6, brush-pins; 7, target ring; 8, epoxy resin.

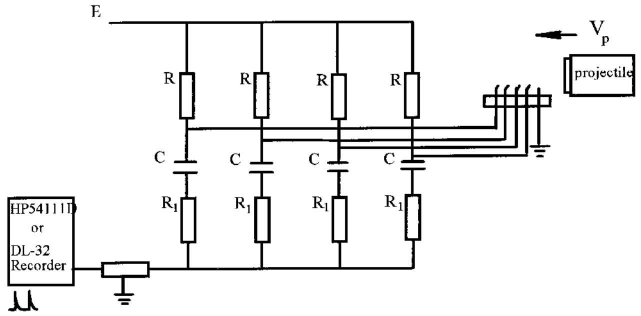

Fig. 2 Diagram of the system for velocity measurement.

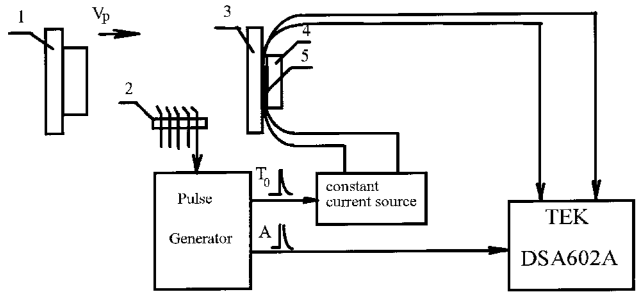

Fig. 3 Diagram of the system for shock pressure measurement. 1, flying plate; 2, brush-pins; 3, target; 4, sample; 5, manganin gauge.

may be controlled and adjusted easily by changing the injected gas pressure.

The shock pressure is measured by manganin gauges that were attached to the interface between the target and the sample. The electricity for manganin gauges is provided by a constant current source (4.5 A).

III. Experimental Results

A. Critical Reaction Pressure by Shock Impact

Critical reaction pressure means the minimum value at which pyrotechnic reaction may occur. Figure 4 indicates the relationship between voltage difference ΔV and time t obtained from the recorded change of resistance of the manganin gauge as a result of the shock wave.

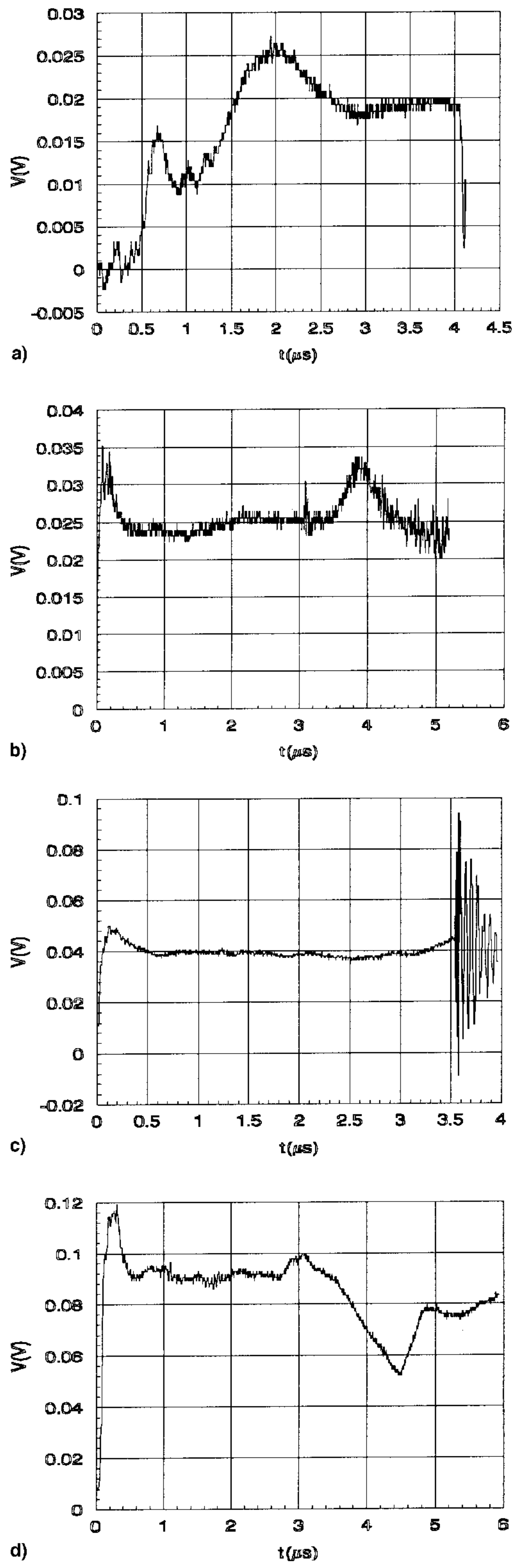

Fig. 4 Curve of $\Delta V - t$ (no. 1 gauge). V_p = a) 198, b) 474.8, c) 548.4, and d) 674.7 m s^{-1}.

On the base of the standardized equation [Eq. (1)] and the known value of initial voltage V_0 of the gauge, the value of shock pressure may be transferred from the measured value of ΔV

$$P = 0.6 + 30.96(\Delta V/V_0) + 21.16(\Delta V/V_0)^2 - 6.61(\Delta V/V_0)^3 \quad (1)$$

Table 1 Projectile velocity and experiment condition

No.	Evaluated velocity, m s^{-1}	Measured velocity, m s^{-1}	Velocity error, %	V_0[a]
1	700	674.7	0.138	1.55[b]
				0.6[c]
				0.69[d]
2	800	——	——	0.5
				0.8
				0.55
3	550	548.4	1.468	0.721
				0.814
4	450	474.8	1.819	0.849
				0.654
5	650	638.0	1.201	0.710
6	850	839.7	1.629	0.607
				0.538
7	200	198	0.829	1.01

[a]V_0 is initial voltage of manganin gauge recorded by oscillogram.
[b]It presents V_0 of no. 1 manganin gauge.
[c]It presents V_0 of no. 2 manganin gauge.
[d]It presents V_0 of no. 3 manganin gauge.

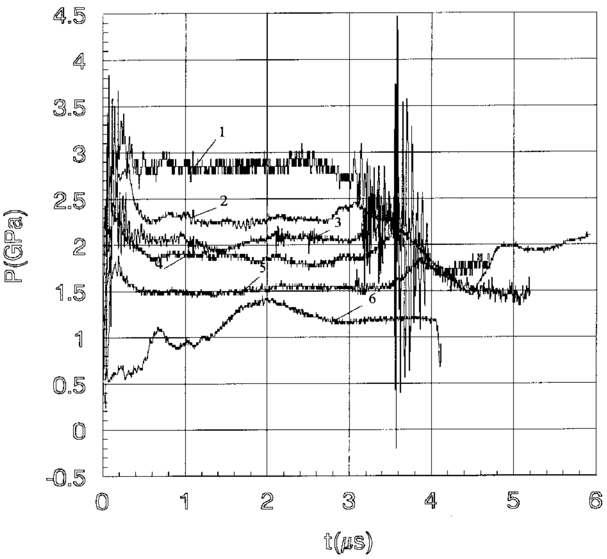

Fig. 5 *P–t* relation with various projectile velocities (for no. 1 gauge). 1, V_p = 839.7 m/s; 2, V_p = 674.7 m/s; 3, V_p = 638.0 m/s; 4, V_p = 548.4 m/s; 5, V_p = 474.8 m/s; 6, V_p = 198 m/s.

Table 1 gives the results of projectile velocities and the experiment condition for seven experiments.

In Table 1, evaluated velocity is the pre-evaluated velocity according to the weight of the projectile and the pressure of gas injected (air or hydrogen), and the velocity error is the maximum relative error between several velocities measured and their average value.

Figure 5 shows the relation between pressure and time for various projectile velocities for a no. 1 gauge (see Fig. 1). It is shown in Fig. 5 that when the projectile velocity is larger than 474.8 m s^{-1}, the laws of changing the shock pressure with time display a similarity. First, when the sample is impacted, the pressure on the sample surface rises from zero to a certain value. After that, the pressure maintains no change for a certain time. Then, the pressure appears to go up to the maximum and then finally decreases. The phenomenon indicates that the decomposition reaction of B–KNO_3 makes the pressure increase. When the projectile velocity is lower than the previously mentioned value, taken, e.g., 198 m s^{-1}, there is no such change. It reflects that there is no decomposition reaction and only an elastic deformation in the sample. From the curves in Fig. 5 the critical reaction pressure of B–KNO_3 under shock impact is approximately determined to be 1.52 GPa.

Table 2 Reaction time delay under different shock pressures

V_p, m s^{-1}	P, GPa	τ, μs
198	1.194	——
474.8	1.52	3.45
548.4	1.829	3.15
638.0	2.055	3.00
674.7	2.295	2.75
776	2.848	2.25
839.7	3.26	——

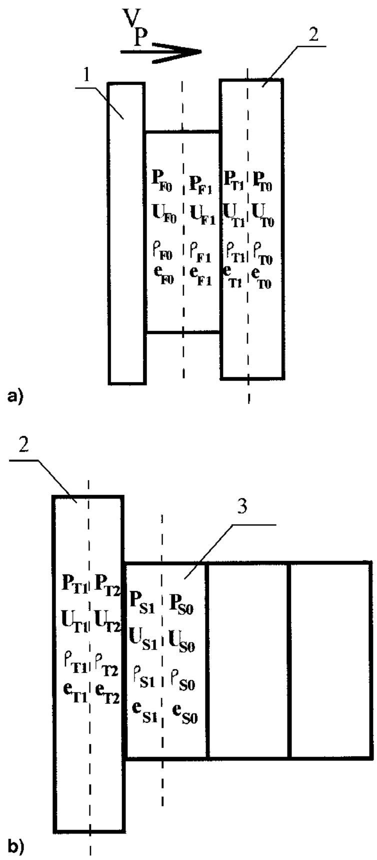

Fig. 6 Diagram of shock wave interface state shock waves arriving at the a) target and b) sample surface. 1, flying plate; 2, target; 3, sample.

B. Time Delay of Chemical Reaction for B–KNO_3

When the sample is impacted by shock after it experiences processes such as breaking-out, motion, and friction between the particles, it decomposes, reacts, or burns. This time interval is called reaction time delay. Table 2 gives the reaction time delay under different shock pressures, and Fig. 5 shows the effects of shock strength on the time delay of B–KNO_3. From Fig. 5 it is seen that the time delay is different as the shock pressure changes and shortens when the velocity of the projectile increases. It must be noticed that there are many factors affecting time delay, for instance, pyrotechnics category, particle size, mixing homogeneity, binder and its percentage, density, and initiation manner. In the present case the delay time corresponding to a critical reaction pressure of 1.52 GPa is about 3.45 μs.

C. Hugoniot Parameters for B–KNO_3

Figure 6 is the diagram of a shock-wave front when a shock wave arrives at a different interface. According to the pressure P_{TS} measured, a resistance-matching method, and continuous conditions on the impacting surface, a set of Hugoniot data for shock waves is obtained and listed in Table 3. Table 3 also

Table 3 B–KNO_3 Hugoniot data

No.	1	2	3	4	5
V_F, km s^{-1}	0.6747	0.776	0.5484	0.4748	0.8397
P_{S1}, GPa	2.295	2.848	1.829	1.52	3.26
u_{S1}, km s^{-1}	0.550	0.630	0.450	0.390	0.683[a]
	0.548	0.635	0.460	0.399	0.689[b]
S, mm	4.70	4.74	4.80	4.82	4.76
	4.70	4.74			
Δt, μs	2.092	2.192	2.282	2.664	1.96
	2.16	2.252			
D_{S1}, km s^{-1}	2.624	2.843	2.556	2.451	3.002[a]
	2.63	2.821	2.501	2.396	2.976[b]
	2.247	2.208	2.103	1.809	2.428[c]
	2.176	2.105			
P_{T1}, GPa	6.383	7.258	5.125	4.406	8.06

[a]Data are obtained by contrast method, which is also called as resistance-matching method or method of extrapolation Hugoniot.
[b]Data are obtained by calculation with shock Hugoniot data of aluminum.
[c]Data are measured with the shock-time arrivals on the gauges.

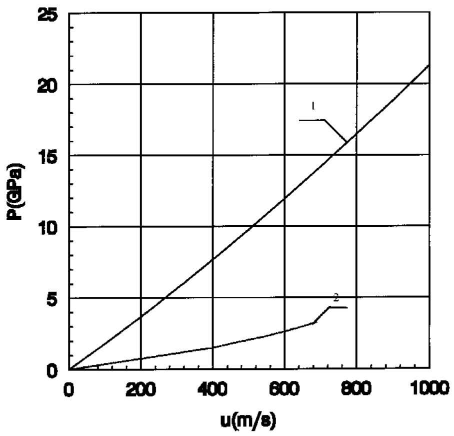

Fig. 7 ***P–u* relation curve 1, AL; 2, B–KNO_3.**

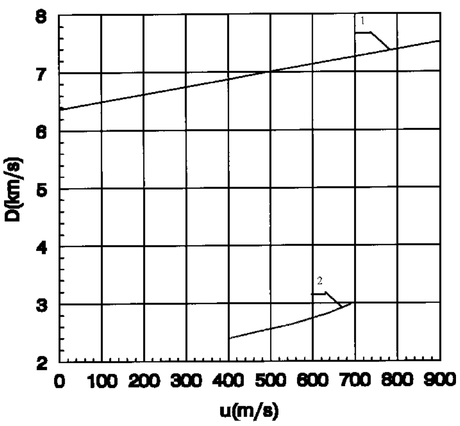

Fig. 8 ***D–u* relation curve. 1, AL; 2, B–KNO_3.**

gives the experimental results of shock velocity in the sample, which are calculated by the sample thickness and time difference of shock arriving at two sample surfaces.

In Table 3, u_{s1}, D_s, P_T, S, and Δt indicate, respectively, the particle velocity obtained on its surface when the sample is impacted, the shock velocity in the sample, the shock pressure on the surface of the target, thickness of the sample, and time difference of the shock wave arriving at two sample surfaces.

From Table 3 it is seen that the experimental results are lower than the results calculated. This may be because there is a space cavity in the sample leading to the decrease of shock pressure. Because of the existence of the packets in the sample of B–KNO_3, when the shock wave travels from the medium with a large resistance to the medium with a small resistance, a rarefaction will be produced. The strength of the shock pressure gradually weakens with the travel of the shock wave in the sample.

Figures 7 and 8 give the P–u and D–u relations of the sample. From the D–u curve it is shown that D and u have a better linear relation under a certain range of shock pressures.

D. Determination of Local Sound Velocity C_0 and the Coefficient λ

On the base of the linear relation of $D = C_0 + \lambda u$, a group of equations may be given for shock waves. Solving the group of superlinear equations, C_0 and λ obtained are, respectively, 1.683 km s^{-1} and 1.773.

IV. Discussion and Conclusions

Experimental studies on the shock initiation of B–KNO_3 were carried out by using a one-stage gas gun and Hugoniot curves for P–t, P–u, and D–u were obtained. Critical reaction pressure and time delay are 1.52 GPa and 3.45 μs, respectively.

The present study confirms the successful use of a one-stage gas gun for the investigation of pyrotechnics' ignition by shock. The advantages are that the important parameters before and after the ignition may be measured or calculated accurately so that the whole process may be investigated more quantitatively. The experiment may also be used to determine the shock sensitivity of pyrotechnics or other energetic materials. Additional information on these aspects may be obtained by comparison with other impact methods.

However, it is seen in Fig. 5 that there is a stronger electrical interference while measuring the signal and it has an effect on recorded P–t curves. Under present experimental conditions the relation between D and u deviates from a linear relation only under a higher pressure range.

The experiment on the gas gun is expensive; therefore in the present investigation only seven experiments were carried out. So the critical reaction pressure obtained is only an initial approximation and further studies are needed. If the parameter ranges in experiments could be extended and carried out at higher pressures and with stronger waves, the outlook for the ignition of B–KNO_3 would be better and more clear.

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