Research paper

Burst phenomenon of spherical firework shell (I)

- Observation of burst phenomenon of firework shell by high-speed photography -

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Abstract

We performed explosion tests on two kinds of firework shells having different diameters (170 mm and 235 mm) and different amounts of bursting charges, etc., in the explosion chamber, and took sequential photographs of explosion and burst phenomenon with a high-speed camera. The obtained photographs first show flames belching out from the joint of a pair of hemispherical shell-packages at the early stage of burst just after the firework shell bursts. Moreover, the photographs prove that a neighboring object adjacent to the firework shell is compressed due to rapid expansion caused by the burst.

Keywords: Firework shell, High-speed photography, Burst phenomenon

1. Introduction

In response to enormous demand for fireworks displays, various kinds of firework shells are produced innumerably not only in Japan, but throughout the world. Under these circumstances, a large amount of firework shells are found in manufacturing facilities and storage facilities. An explosion occurring at such a facility storing a large amount of fireworks often leads to the chain-explosion of firework shells, eventually leading to a large-scale explosion marked by serial and extensive damages. We observed the explosive-to-explosive propagation of explosion. An explosion phenomenon where explosion rapidly spreads from one explosive to another is sometimes called “sympathetic detonation”.

An important consideration in developing safety plans and a method for preventing sympathetic detonation is to investigate and understand the mechanism of sympathetic detonation in detail. However, little research has been conducted on the explosion process and sympathetic detonation. Our long-term goal is to clarify the mechanism of sympathetic detonation. As is evident, the initial explosion of an explosive (donor) shell induces an explosive reaction (sympathetic detonation) of another explosive (acceptor). Understanding the conditions that lead to sympathetic detonation, we should verify processes and effects of the explosion of the donor in detail.

To date, several studies[1)~4)] have been carried out on the burst phenomenon of a firework shell. However, fundamental information (e.g., destruction processes of shell case, pressure within[4)] and outside the shell at burst, etc.) about the burst phenomenon of a firework shell remains unknown, particularly information about the initial processes of bursting of a firework shell.

In this experiment, as a first step towards understanding sympathetic detonation, we performed an explosion test using one firework shell per shot, in order to clarify the burst processes of a firework shell by high-speed photography.

2. Experimental setup

This experiment was performed in the explosion chamber at AIST. The chamber is similar in shape with a medicine capsule, and measures 5 m in inner diameter and 8.2 m in height. Figure 1 shows the experimental setup of

Table 1 Specifications of firework shells.

Shot No.	Shell name	Shell size* (mm)	Weight (kg)	Case		Fuse-length (mm)	Bursting charge** (kg)	Star		
				Outer diameter (mm)	Inner diameter (mm)			Average outer diameter (mm)	Average weight (kg)	Number
6a-1	Three-color changing 170 mm shell	170	1.84	165	158	49	0.437	16.5	0.0036	238
6a-2	Three-color changing 170 mm shell	170	1.84	165	158	49	0.437	16.5	0.0036	238
6a-3	Three-color changing 170 mm shell	170	1.84	165	158	49	0.437	16.5	0.0036	238
8a-1	Three-color changing 235 mm shell	235	4.00	221	210	58	0.815	21.0	0.0064	286
8a-2	Three-color changing 235 mm shell	235	4.00	221	210	58	0.815	21.0	0.0064	286

* Including the thickness of facing-paper ** Not including inert material such as cork and cotton

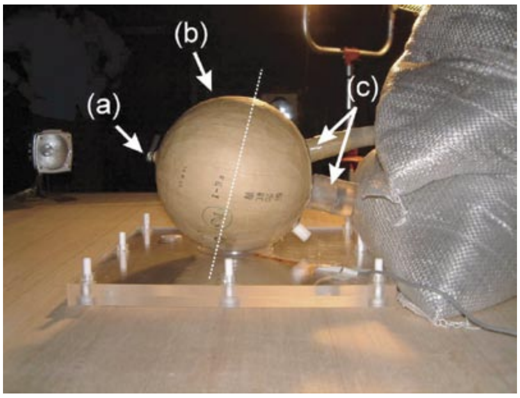

Fig. 1 Experimental setup. The dotted line indicates the joint portion between a pair of hemispherical shell cases. (a) Fuse, (b) Shell case, (c) Sensors for measuring internal pressure.

Table 2 Chemical composition of bursting charge of the firework shells used in this experiment.

Chemical composition	Weight %	
	170 mm firework shell	235 mm firework shell
Potassium perchlorate	69	48
Potassium nitrate	7	22
Charcoal (hemp)	21	26
Paste	3	4

the firework shell assembly we used in our experiment. Specifications of the firework shells we used are summarized in Table 1. We used two kinds of firework shells, both called three-color changing, but having different diameters and different amounts of bursting charges, etc. (see Table 1). A firework shell consists of a pair of packages each having a hollow, hemispheric shape; a bursting charge (see Table 2); and numerous stars (see Table 1). The stars consist primarily of potassium nitrate, potassium perchlorate, strontium carbonate, barium nitrate, charcoal, etc. The bursting charge was set in the center of the pair of packages. The stars inside the packages were packed closely around the bursting charge. The two packages filled with bursting charge and stars were joined together, and many pieces of Kraft-paper were pasted in layers outside of the packages, in order to provide the shell with extra strength.

The firework shell was placed on a wooden table in the explosion chamber, then ignited by firing a fuse with firing

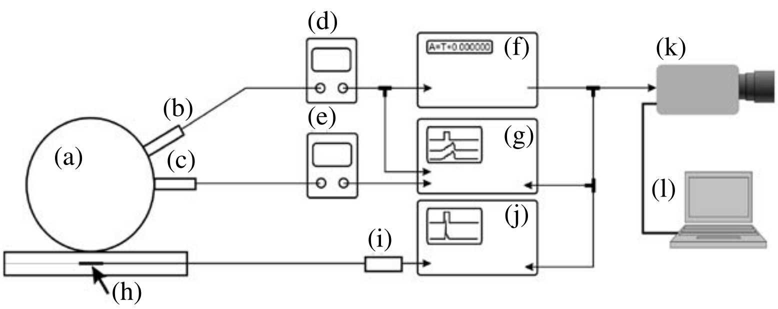

Fig. 2 Schematic configuration of electrical wiring of measurement instruments.
(a) Firework shell, (b) Piezoelectric pressure sensor (HM113A22, PCB Piezotronics, Inc.), (c) Piezoelectric pressure sensor (HM102A, PCB Piezotronics, Inc.), (d)(e) Signal conditioner (480D02, PCB Piezotronics, Inc.), (f) Digital delay/pulse generator (DG535, Stanford Research Systems, Inc.), (g) Digital oscilloscope (DS-8812, Iwatsu Test Instruments Co.), (h) Piezoelectric stress gauge (PVF2-11-0.25-EK, Dynasen, Inc.), (i) Charge integrator (CI-50-0.01, Dynasen, Inc.), (j) Transient waveform digitizer (RTD710A, Tektronix, Inc.), (k) High-speed camera (Phantom V5.0 color-model, Vision Research Co., Ltd.), (l) Computer.

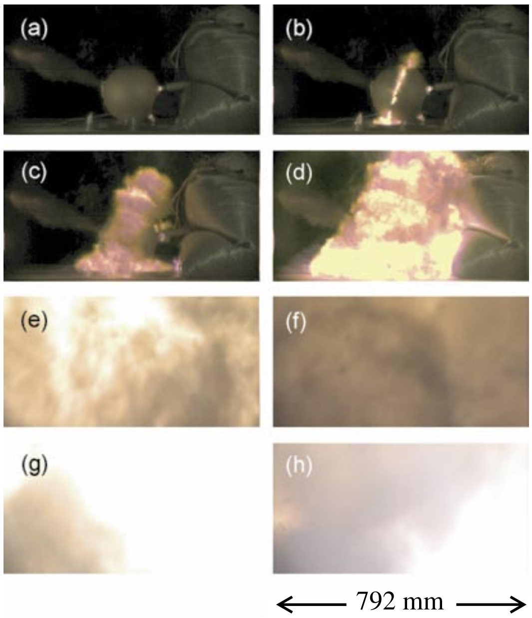

Fig. 3 High-speed framing photographs of burst phenomenon of 170 mm shell (Shot No. 6a-1). (a) 0.223 ms, (b) 0.362 ms, (c) 0.500 ms, (d) 0.639 ms, (e) 2.167 ms, (f) 4.945 ms, (g) 9.112 ms, (h) 17.445 ms after trigger. Time zero denotes the trigger time of the high-speed camera.

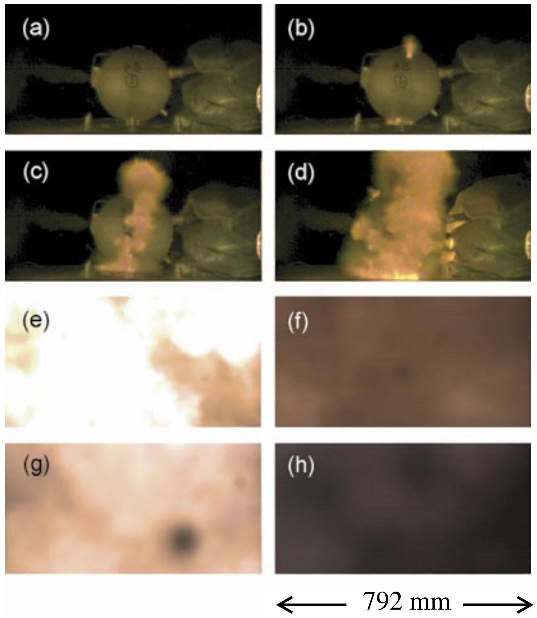

Fig. 4 High-speed framing photographs of burst phenomenon of 235 mm shell (Shot No. 8a-1). (a) 0.366 ms, (b) 0.505 ms, (c) 0.644 ms, (d) 0.783 ms, (e) 1.477 ms, (f) 4.810 ms, (g) 8.144 ms, (h) 11.477 ms after triggering.

powder and a firing system (DX-100-D, NOF Co.). The firework shell exploded within a few seconds after firing the fuse; the delay time from firing to explosion depends on the length of the fuse.

Figure 2 is a schematic diagram of electrical wiring for measurement instruments. Burst phenomena were recorded by a high-speed digital color video camera "Phantom V5.0" (Vision Research Co., Ltd.), using a lens "Nikkor 35 mm F1.4S" (Nikon Co.). Two 500-watt bulbs (LPL Co., Ltd.) were used for illuminating the firework shell. As a result, lighting intensity on the surface of the shell was about 40,000 lux. Camera settings were as follows: number of pixels - 256(vertical)×512(horizontal); recording rate - 7200 frames per second; exposure time - 50 μs; and lens iris - f1.4 (open). Total recording time was about 1.1 seconds. The field of view measured 396 (vertical)×792 (horizontal) mm. Consequently, spatial resolution was 1.55 mm.

The trigger pulse for the high-speed camera was supplied from a digital delay pulse generator "DG535" (Stanford Research Systems, Inc.). Time zero (t=0) denotes the time when the output from the internal pressure sensor reached 0.3 volts, corresponding to an internal pressure of 2.0 MPa. Timing jitter and internal delay time of the pulse generator were negligibly small (typical values: 50 ps and 85 ns, respectively).

3. Results and discussion

Figures 3 and 4 show typical photographs of the burst phenomenon for the 170 mm shell and the 235 mm shell, respectively. The obtained photographs show flames belching out from the shell joint at the early stage of bursting. The time when the flames belch out from the shell corresponds to the beginning of shell burst. The burst of the 170 mm shell occurred at 0.338±0.069 ms after triggering,

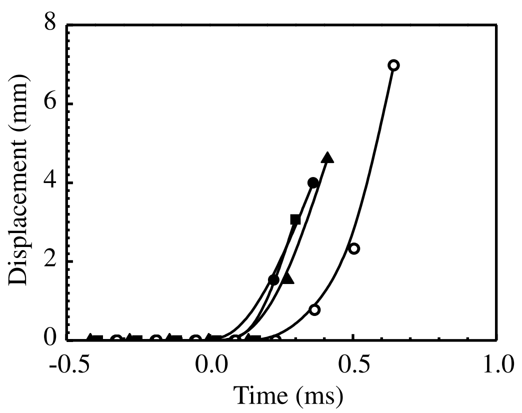

Fig. 5 Temporal change in radial displacement of firework shell. ●:6a-1, ▲:6a-2, ■:6a-3, ○:8a-1 are experimentally obtained data, parallel to the horizontal axis. The solid lines are provided as guides.

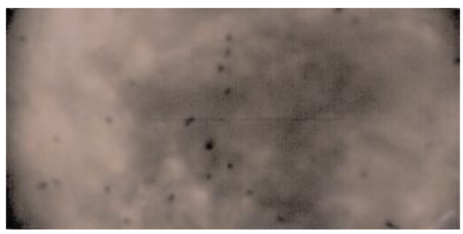

Fig. 6 High-speed framing photograph of 235 mm shell taken at 3.479 ms after burst (Shot No. 8a-1). Black dots observed in this picture are fragments dispersed from the firework shell.

and showed reproducibility. The burst of the 235 mm shell occurred at 0.485±0.069 ms after triggering. The high-speed camera could not capture the entire rupture process of the shell, because soon after the burst the flames rapidly began to cover the shell.

Just before the burst, expansion of the shell case could be observed. During shell case expansion, radial displacement of the shell case seems to differ from position to position. Displacement is large at the horizontal axis, whereas no clear displacement is observed at the vertical axis. Figure 5 shows temporal change in radial displacement at the horizontal axis of a firework shell. The amount of radial displacement increases almost linearly with time. Assuming that the expansion velocity of shell case is constant before the shell is covered with flames resulting in a burst, velocity could be estimated at about 20 ms^{-1} for both shell sizes.

After the shell burst, the flame takes about 0.5~0.6 ms to spread over the field of view (width 792 mm). The expansion velocity of the flame was recorded at 600~800 ms^{-1}, not taking into account the flame's expansion in the depth direction toward the high-speed camera. In the experiment with the 235 mm shell, a photograph taken at 3.479 ms after burst (see Fig. 6) shows that a lot of fragments came out from inside the flames. Observed fragments were dispersed in a three-dimensional space, making precise determination of fragment velocity impossible.

Although after a few milliseconds the emission of the flames belching out from the shell diminished for a while, new flames (see Fig. 3(g), Fig. 4(g)) appeared within about 10 ms after trigger. This phenomenon raised the possibility that the effects of secondary combustion of bursting charges etc. had occurred. Furthermore, a lot of spherical objects, which obviously were stars, and many fragments of irregular shape were scattered in all directions. Around this time range, the shell case was considered to be almost completely broken into many fragments. Whether or not the stars that were scattered due to bursting were lighted at this time range is unclear, because the stars were reflected black in the photographs.

In addition, we confirmed that the pressure sensors with the attachment that we used had been mounted on the shell case firmly until just after the burst of the firework shell. That is to say, this result indicates that use of the attachment is highly likely to enable measurement of the pressure inside the shell.

Considering the manufacturing methods and structure of a firework shell, the thinnest part of the firework shell case serves as a portion connecting the two hemispherical shell packages. The strength of this joint portion depends simply on the number of pieces of Kraft-paper pasted on the shell case, and this portion is supposed to exhibit the lowest rupture strength. Naturally the burst is assumed to originate at the portion of the lowest strength. This simple assumption agrees well with the experimental results (see Fig. 3 and 4). However, a lot of small fragments were recovered after the explosion test.

The following are the noteworthy findings derived from the high-speed photographs:

1. The burst of firework shell begins to occur at the joint portion between the pair of hemispherical shell packages. That is, the photographs clarified that the firework shell ruptures in non-spherical symmetry at the early stage of burst.
2. The shell case apparently ruptures symmetrically, in view that fragments recovered after the explosion test were numerous and varied in shape.
3. In the firework shells we used in this experiment, the stars ejected by the burst generally disperse in spherical symmetry. The shell case also spreads outward in spherical symmetry. Consequently, the shell case is considered to be homogeneously broken into fragments.

Reconciling the three above findings is difficult, unless we suppose that several burst processes occur during the period during which the phenomenon of the findings are observed. When flames are belching out from the bursting firework shell, the combustion gas is blown out of the shell, thereby lowering internal pressure. Meanwhile, unburned bursting charges continue to burn even after the burst, generating combustion gas that increases internal pressure. Therefore, net internal pressure after burst depends on both the amount of increase in combustion gas and the amount of decrease in combustion gas. Thus, assuming that the rate at which internal pressure increases from burning charges is greater than the rate at which pressure drops as a result of escaping combustion gas, we could suppose that the cracks originate at the joint portion and rapidly propagate over the shell case. As a result of the pressure continuing to increase after the burst, the shell case is eventually broken up into many fragments. Moreover, the stars have higher density than the shell case; therefore, assuming that the shell fragments and stars are of the same size, the shell case fragments would be accelerated more quickly than the stars. As described above, the following explosion processes are considered to occur. The shell case, having been divided into numerous fragments, precedes the stars in expanding along with the combustion gas belching out from the shell. Afterward, the stars, undergoing slow acceleration, are ejected outward in all directions without any interference by the shell case fragments.

4. Conclusions

In this work, explosion tests with two kinds of firework shells were performed in order to clarify the burst processes by high-speed photography. The following conclusions can be derived from the obtained results. For the first time, we obtained photographs that show flames belching out from the joint portion of a pair of hemispherical shell-packages at the early stage of burst just after the firework shell bursts. Obtained photographs show that the burst originates at the portion of the shell case exhibiting the lowest strength. The fragments recovered after the explosion test are numerous and varied in shape, suggesting that the cracks initiate at joint portion and rapidly propagate over the shell case. The shell case is broken up into many fragments within a few milliseconds, due to the pressure continuing to increase for a certain time after the burst.

For more detailed analysis and accurate understanding of the burst processes of firework shells, similar experiments must be carried out while varying shell diameter, shell case thickness, amount of bursting charge, etc.

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球形煙火玉の開発現象（第1報）

－高速度撮影による煙火玉の開発現象の観察－

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直径 170 mm 及び 235 mm の球形の煙火玉を爆発チャンバー内で爆発させ，爆発状況を高速度カメラで撮影した。本実験で使用した煙火玉の場合，開発の初期段階において玉皮の合せ目部分から火炎が噴出している様子が初めて撮影され，開発が玉皮強度の低い部分から進行することが確認された。さらに，開発の直前に煙火玉が急峻に膨張する様子が観測され，隣接する物体を圧縮していることが明らかとなった。

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