Research paper

Combustion properties of grain black powder used as a lifting charge of fireworks

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Abstract

The flame temperatures of burning grain black powder and meal black powder were measured with a thermocouple and the flame spread behavior was observed with a high speed camera in this work. Because black powder-grains are involved in the flame and move through a longer distance with burned products, the powder-grain burns up far behind the flame and the apparent burning reaction zone become wide. The flame spread rate of grain black powder is very fast. On the other hand, the flame of the tightly charged meal black powder retreats to the non-burning zone in parallel as the burning wave front keeps a plane and the flame spread rate is slow. Also, influences of the ambient pressure and the grain sizes of grain black powder on the mass burning rate were examined in this work.

Keywords : black powder, lifting charge, fireworks, combustion, flame

1. Introduction

Black powder, although dating back to ancient days, is still used as a propellant, blasting agent and igniter. Also, as the major firework ingredient, its use remains unsurpassed. Especially, it is used as lifting charge of a firework shell because the burning of grain black powder is very fast. The muzzle velocity of firework shell depends on the combustion properties of lifting charge and the pressure in a mortar because the shell is launched by the pressure of product gas of lifting charge.

Since there is a gap between mortar and firework shell, the combustion gas of lifting charge leaks around the shell. The effects of combustion gas leakage from the lifting charge on the shell dynamics in a mortar were qualitatively examined by the analysis of pressure-time curves measured with more than one pressure sensors, which were installed along the mortar in the previous papers[1-2]. Also, the relationship between shell dynamics and combustion gas leakage was analyzed by calculating the pressure rise rate-time profiles from the pressure-time profiles measured at the bottom of a mortar. Moreover, the method of calculating the muzzle velocity with a good precision was verified in the past papers, even in the case of a large amount of product gas leakage from the gap.

There have been some research papers about theoretical research of firework shell ballistics[3-4]. However, the internal ballistics calculation of a firework shell is very difficult because there is little information about the combustion behavior of grain black powder as a lifting charge and it is very difficult to build the burning model correctly for a lifting charge.

For a much more comprehensive understanding of the burning behavior of grain black powder used as a lifting charge, the burning and the flame spread behavior of grain black powder and meal black powders was observed by using a high speed camera and the combustion temperatures were measured with a thermocouple in this research work. Moreover, the influences of ambient pressure and the grain sizes of grain black powder on mass burning velocity of the black powder in a closed tank were examined.

2. Experiments

2.1 Samples

The grain black powder used in the experiment is the commercial grade for the firework lifting charge, which is made by Nippon Kayaku Corporation. The meal black powder is the one which is the crushed sample of the grain black powder that passed a 150 μm sieve. However, the chemical components of both samples are the same.

2.2 Burning test inside transparent tube

A grain black powder or a meal black powder was charged into a transparent pipe which is made from acrylic resin, with 8 mm inner diameter and 20 mm length, respectively. After ignition from the sample upper part, the burning of the black powder and the state of the flame propagation was recorded simultaneously by using a high speed camera. The camera speed was set at 1,200 frames per second.

2.3 Flame temperature measurement

Schematic diagram of flame temperature measurement is shown in Figure 1. A grain black powder or a meal black powder was charged into the aluminum pipes with 6 mm inner diameter, 10 mm external diameter and 90 mm length, respectively.

Three holes along the aluminum pipe in the 30 mm interval from the 20 mm the pipe upper to the pipe bottom (marked with A, B, C in the figure) were opened and K-type thermocouple with 100 μm of wire diameters was inserted into each hole for measuring the flame temperature. The outputs from the thermocouple were recorded by an oscilloscope with 10 kHz sampling rate and the temperature-time curves were obtained.

2.4 Closed tank test

A grain black powder or a meal black powder was charged into the aluminum pipe with 9 mm inner diameter, 11 mm external diameter and 30 mm length, respectively.

After making a nichrome wire touch a sample upper part, the sample was set vertically inside the closed tank. After igniting the sample by applying an electric current to the nichrome wire, the pressure produced by burning gas in the tank was measured simultaneously with a pressure sensor. The volume of the closed tank is approximately 1.1 liters. The schematic diagram of the closed tank experiment is shown in Figure 2. The experiments were conducted under the condition that the gauge pressure in the closed tank was set to about 100 kPa (above atmospheric pressure), 0 kPa (atmospheric pressure), −40 kPa (reduced pressure) or −20 kPa (reduced pressure). The ambient pressure was 200 kPa, 100 kPa, 60 kPa or 20 kPa in absolute pressure, respectively.

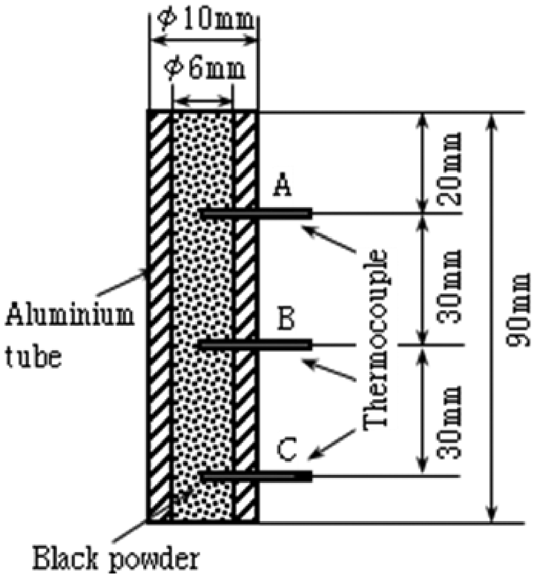

Figure 1 Setup of temperature measurement.

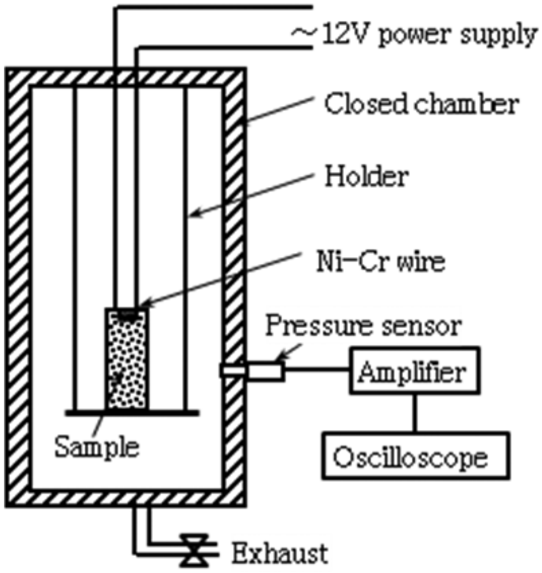

Figure 2 Setup of closed tank test.

Moreover, to examine an influence of the grain size, the grain black powder was passed through several sieves in the order of sieve mesh from large mesh to small mesh and each group of the black powder-grains which stayed at each sieve was collected. The collected grain black powders were tested in the same method as described above. However, the tests were only carried under the atmosphere pressure (about 100 kPa absolute pressure).

The charge densities of the grain black and the meal black powder were approximately 1.02~1.08 g cm^{-3} and 1.11~1.15 g cm^{-3}, respectively.

3. Results and discussions

3.1 Burning and flame spread behavior of black powder

The pictures of burning and flame spread of the grain black powder and the meal black powders are shown in Figure 3. The pictures were cut out from the video taken by a high speed camera. The pictures show that the front of the burning flame is transformed gradually after the ignition, followed by the occurrence of disorder, the deformation of the flame surface and then the enlargement of the flame surface area in case of the grain black powder. The flame consisted of hot combustion products. From the analysis of the video, it was found that the flame propagated into the openings or gaps among the grains of the grain black powder, so that the powder-grains ignited and burned as they were engulfed by the flame one after another in many groups. Also, the powder-grains continued to burn in the flame while flowing with the burned gases in the direction opposite to that of the

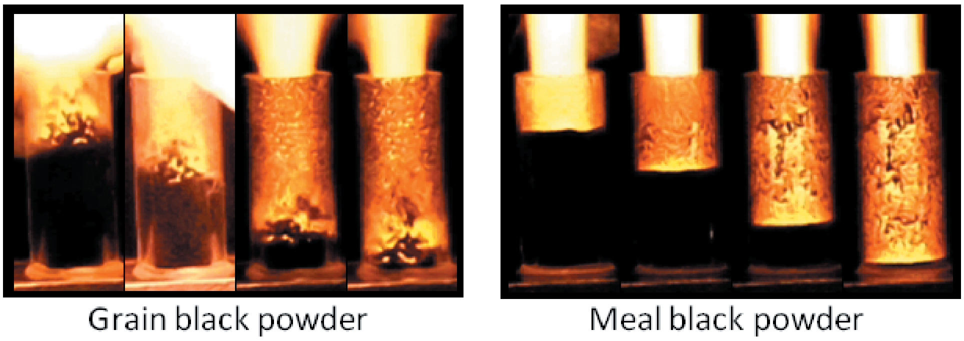

Figure 3 Photographs of burning black powder.

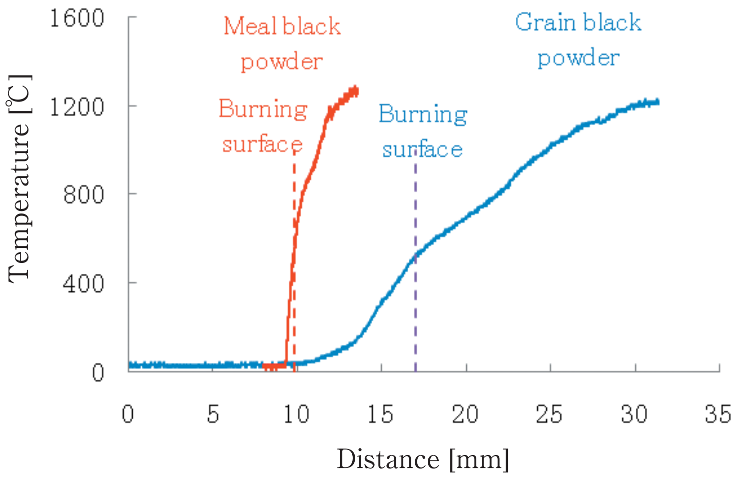

Figure 4 Temperature profile of grain and meal black powder.

flame propagation. Combustion occurred at the surface of each black powder-grain in the flame. Therefore, as for the combustion of grain black powder, it is found that the flame propagates from one powder-grain to another, and the burning occurs simultaneously at the surface of each powder-grain. For each grain, the burning progresses inwards from the grain surface, so the burning surface area of the whole flame is a summation of all of the surface area of each powder-grain which is burning in the flame.

On the other hand, as for the combustion of the meal black powder, the burning surface or wave retreated quietly to the non- burning black powder in parallel as it kept a plane and the burning area was approximately the same as the cross-section of the pipe.

The experimental results show the following remarkable difference in combustion characteristics for both grain black powder and meal black powder. As for the former, the grain burns and moves a long distance spatially with the burned gas while it is ignited in the flame. As for the latter, the fine meal powder burns up in a thin layer in the flame and hardly moves spatially.

3.2 Structure of the flame

The combustion temperature of black powder was measured by a K-type thermocouple that was inserted into the black powder. An example of the temperature-distance profile is shown in Figure 4. The horizontal axis indicates the distance, which is the multiplication of the time in temperature-time curve by the flame propagation speed. The flame temperature-distance profiles of a grain black powder and a meal black powder are shown by a blue line and a red line in this figure, respectively.

The plane flame surface of the meal black powder can be visualized in Figure 5. The flame zone can be roughly divided into two zones: the preheating-zone and the reaction-zone. Upon entering the preheating-zone, non-burning black powder is heated by the heat from the reaction-zone, and the temperature rises from initial temperature T_0. When the temperature rises up to temperature T_i, which is the burning surface temperature, the gas phase reaction begins to take place. It is possible to assume that this temperature is an ignition temperature, and a reaction zone begins from the point. A large amount of reaction heat is generated because of the chemical reaction in the reaction-zone, and its temperature increases. This chemical reaction ends at a certain distance from the burning surface temperature. The width of this reaction-zone can be assumed as the thickness of the flame. The temperature T_f attained in the reaction-zone should agree with the adiabatic temperature of combustion if there is not any heat loss. The adiabatic temperature of combustion for black powder is about 1770 K (1497 °C) according to the chemical equilibrium computation[5]. This is the theoretical calculation result with the assumed ideal conditions that the ingredients in black powder mix uniformly in the molecular level and the heat loss is ignored. But actually, black powder is a heterogeneous system which consists of three kinds of different solid materials. Each material consists of fine particles with the order of 10 μm in diameter, and the

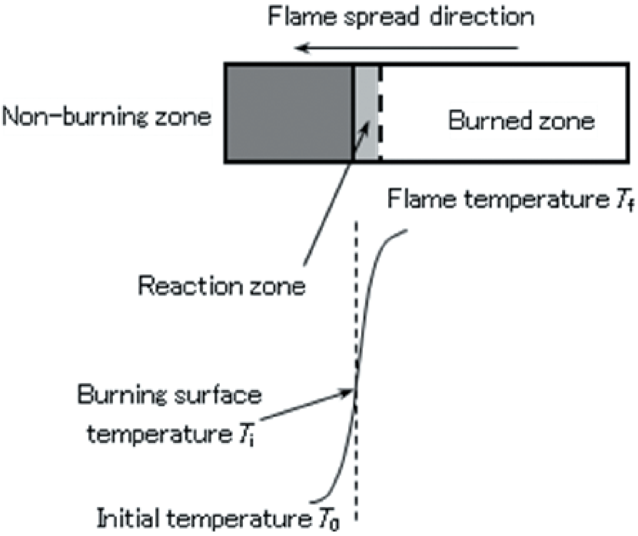

Figure 5 A schematic diagram for the burning meal black powder.

black powder itself is not a homogeneous system in molecular level. There is some heat loss during combustion, too. Because of the above reasons, the actual combustion temperature of black powder should be lower than the theoretical calculation value.

The flame of grain black powder, which consists of the burning of powder-grains, is different from that of meal black powder. As for the individual powder-grain of grain black powder, the burning reaction mechanism that occurs on the grain surface is same as tightly charged meal black powder mentioned above. However, the temperature profile measured with the thermocouple is not an individual powder-grain combustion temperature and is the temperature profile of the whole burning flame consisting of all of the burning powder-grains in the flame. Schematic diagram of the temperature profile (blue line in Figure 4) of the grain black powder can be described in Figure 6.

It is suggested that the grains of grain black powder burn further behind the flame and the apparent burning-zone becomes wider and the apparent thickness of the flame becomes larger than that of the meal black powder. On the other hand, tightly charged meal black powder instantly burns up when entering into the flame and the reaction zone becomes narrow and the thickness of the flame becomes thin with about several mm. The results agree with the phenomenon that is observed by the high speed camera.

3.3 Flame spread rate

The spread time of flame passing two thermocouples along the pipe can be obtained from the two temperature-time curves, and an average flame spread rate can be determined with the distance between two thermocouples being divided by the spread time.

The flame spread rates of the grain black powder and the meal black powder are shown in Table 1.

The results shown in Table 1 indicate that the flame spread rate of the meal black powder is approximately constant, but the flame spread rate of the grain black powder tends to accelerate gradually. Also, the flame spread rate of the grain black powder is about 20 - 30 times as fast as that of the meal black powder.

For comparison, the burning rate of meal black powder measured at 1 atm by Sasse[6] is also shown in this table. According to Sasse's data, burning rates of black powder decrease linearly with an increase of apparent density. Therefore, our experimental result for burning rates of meal black powder is comparable to that of Sasse's report when apparent density is the same.

If the moving distance of burning surface can be determined by one piece of independent space coordination except time, the burning can be assumed one-dimensional regardless of the flame shape (plane, column surface, spherical surface and so on) of the burning surface, and the combustion can be expressed using a linear burning rate. Such a burning phenomenon is called a

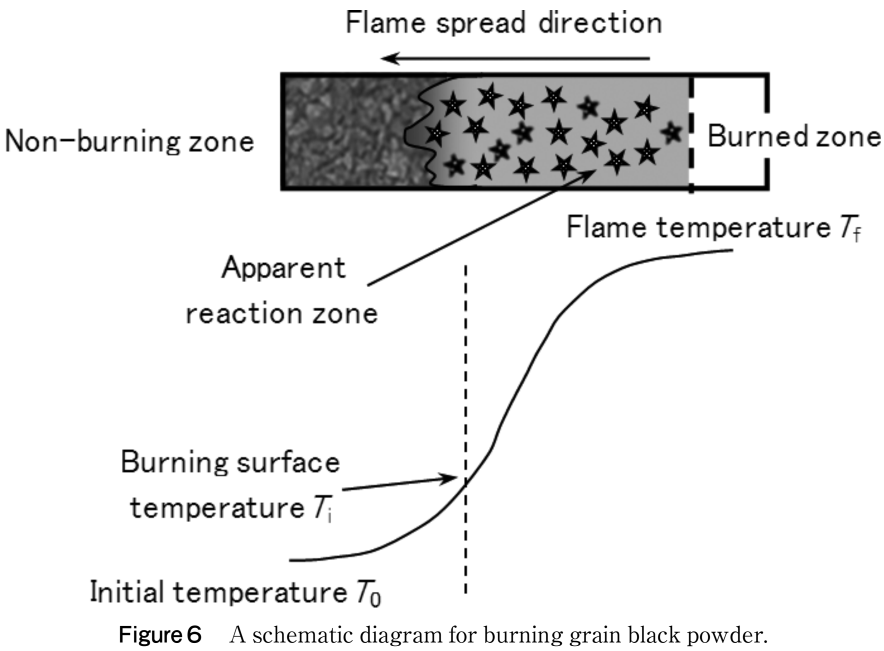

Figure 6 A schematic diagram for burning grain black powder.

Table 1 Flame spread rates of black powder at 1 atm.

	From A to B [cm s^{-1}]	From B to C [cm s^{-1}]	Charge density [g cm^{-3}]
Grain black powder (not classified by sieves)	29.4	48.0	1.02~1.08
Meal black powder	1.41	1.45	1.11~1.15
Meal black powder from Sasse[6]	1.0		1.3

cigarette burning. Linear burning rate is equivalent to the distance normal to any burning surface of a propellant grain burnt through in unit time according to R. Meyer[7].

The burning of a tightly charged meal black powder is a cigarette burning and the flame spread speed is equal to linear burning rate.

With regard to an individual grain black powder, because the flame on the powder-grain surface moves inwards in the direction perpendicular to the surface of the grain, it is possible to assume that the grain burns one-dimensionally, therefore the burning surface moving rate for each burning grain is equal to the linear burning rate. However, the whole flame propagation cannot be assumed one-dimensional for a grain black powder, since the whole flame spreads through a powder-grain from another powder-grain and the flame front is transformed gradually. Therefore, the whole flame spread rate of a grain black powder cannot be merely expressed by linear burning rate. As a substitute, it is appropriate to use mass burning rate to evaluate the burning rate of a grain black powder.

3.4 Influences of ambient pressure on mass burning rate

Assuming that the onset of pressure increase in the pressure-time curve is the onset of burning and the time at peak pressure is the end-set of burning, the time difference gives the burning time of the sample in the closed tank test. The value of the sample mass divided by the burning time is the mass burning rate. Mass burning rates for a grain black powder and a meal black powder with different ambient pressures in the closed tank are shown in Figure 7. The horizontal axis gives the absolute pressure in the closed tank.

The relationship between mass burning rate and ambient pressure shown in Figure 7 can be fitted by the following equation.

$$r_m = \alpha \left(\frac{P}{P_0} \right)^{\beta} \qquad (1)$$

Where r_m ($= dm/dt$) is the mass burning rate in grams per second, α is the constant, β is the pressure exponent, P is the pressure, and P_0 is the atmospheric pressure (about 100 kPa absolute pressure). The values of α and β for both black powders are indicated in Figure 7.

The mass burning rate r_m increases when the ambient pressure P increases for both black powders. However, the mass burning rate of the grain black powder is an order of magnitude faster than that of the tightly charged

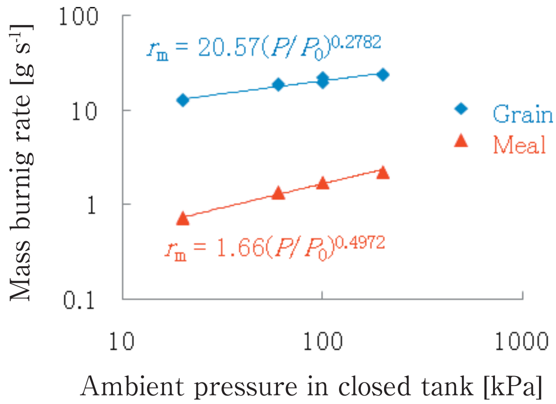

Figure 7 Relationship between mass burning rate and ambient pressure.

meal black powder. The reason is possibly because the flame front is easy to penetrate and heat the openings or gaps among the grains of grain black powder or among the powder-grains.

3.5 Influences of grain size on mass burning rate

The grain size of the grain black powder used for a lifting charge, which is classified according to the mesh sizes of sieves, is shown in Table 2 in weight percent (wt %).

The relationship between mass burning rate and grain size of grain black powder obtained with closed tank tests is shown in Figure 8. The horizontal axis displays grain size by class.

The experimental results show that the larger the grain size, the quicker mass burning rate of the grain black powder.

It could probably be due to the fact that the front of flame is easy to penetrate the larger openings or gaps among the powder-grains of the grain black powder because the gaps among the grains are large when the grain size is large.

Table 2 Size distribution of grain black powder.

Sieve mesh	Weight percentage [%]
Below 300 [μm]	0.04
300~425 [μm]	0.97
425~600 [μm]	16.30
600~850 [μm]	40.95
850μm~1.00 [mm]	32.71
1.00~1.18 [mm]	9.03

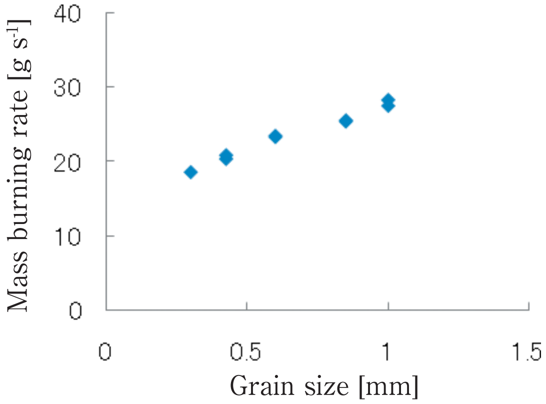

Figure 8 Mass burning rates of black powder with various grain sizes.

3.6 Mass burning rates of grain black powder used as a lifting charge

The relationship of mass burning rate of grain black powder, the burning surface area, the density of powder-grain, and the linear burning rate of powder-grain can be expressed by the following equation.

$$\frac{dm}{dt} = S\,(t)\cdot\rho\cdot r_b \qquad (2)$$

Where m is the charge mass, ρ is the powder-grain density and r_b is the powder-grain linear burning rate. $S\,(t)$ is the sum of the surface area of all of powder-grains which is burning in the flame at the time t. If the powder-grain is spherical, the total burning surface area can be expressed by $S\,(t) = \sum_i N_i\,(t)\cdot\pi d_i\,(t)^2$. Here, $N_i\,(t)$ and $d_i\,(t)$ are the number and the diameter of the powder-grain in the flame, respectively. The subscript i means the grain group which has an identical diameter.

On the other hand, the equation (2) can also be applied to the tightly charged meal black powder. In the case of charging meal black powder tightly into a container, ρ is the charging density, and r_b is the linear burning rate which is equal to the flame spread rate. $S\,(t)$ is the burning surface area, and it is equal to the cross-sectional area of the container when the flame spreads in a perpendicular direction to the cross-section of the container.

The experimental result in closed tank test shows that the mass burning rate of the grain black powder $\frac{dm}{dt}$ is an order of magnitude faster than that of the meal black powder. If the density of tightly charged meal black powder is the same as that of the powder-grain, the linear burning rate of the meal black powder is equal to that of the powder-grain. As for tightly charged meal black powder, the linear burning rate is slow, and it burns in the thin layer in the flame where the flame surface area is the same as the cross-section of the container, therefore the value of $\frac{dm}{dt}$ is small. On the other hand, in case of the grain black powder, the flame spread rate is much faster than the linear burning rate of powder-grain and there are a lot of the burning powder-grains in the flame. The actual burning area is larger than the container cross-section area, therefore, the value of $\frac{dm}{dt}$ is large.

Mass burning rates of the grain black powder obtained in this research are the experimental results in each case of charged sample in the container with 30 mm length and 9 mm inner diameter and the ignition is taken at the upper part of each sample. However, since the propagation characteristics of the flame changes with the size and the shape of the container in which the sample is charged and the position of the ignition, mass burning rate, too, changes.

It is important to correctly model the burning of lifting powder in order to predict the shell dynamics in a mortar. If the equation (2) is used to model the burning characteristics of the lifting charge, the powder-grain density ρ and the powder-grain linear burning rate r_b are easily determined by an experiment. However, it is very difficult to correctly determine the total burning surface area $S\,(t)$ in equation (2). This is because the burning characteristics of the lifting charge placed in the mortar and the propagation characteristics of the flame are very complicated.

There are some research papers for predicting firework shell internal ballistics[3),4)]. However, literatures of correctly modeling the pressure-time curve and the movement of a firework shell in a mortar could not be readily found. The main reason is that there is very little information about the total burning surface area $S\,(t)$ for a lifting charge.

It is possible to correctly find $S\,(t)$ by measuring the actual pressure profile in a mortar and investigating the burning behavior of lifting charge. This is a research theme in the future.

4. Conclusions

The main conclusions are obtained as follows about the combustion properties of the grain black powder and the meal black powder in this work.

(1) The burning of a grain black powder occurs at the surface of each powder-grain and the burning powder-grain burns further behind the flame, and the apparent burning zone is wide.

(2) The flame spread rate of a tightly charged meal black powder is stable and is approximately constant. On the other hand, the flame spread rate of grain black powder tends to be remarkably faster and it also tends to be accelerating.

(3) Mass burning rate of grain black powder is about an order of magnitude faster than that of tightly charged meal black powder and is largely influenced by the ambient pressure.

(4) The larger the grain size of grain black powder, the faster the mass burning rate.

References

1) D. Ding, M. Higaki, Y. Ooki, and T. Yoshida, Sci. Tech. Energetic Materials, 67, 164 (2006).
2) D. Ding, M. Higaki, Y. Ooki, and T. Yoshida, Sci. Tech. Energetic Materials, 72, 164 (2011).
3) T. Shimizu, Selected Pyrotechnic Publications of Takeo Shimizu, Part 1, Journal of Pyrotechnics, Inc. (1997).

4) John E. Mercer, J. Pyrotechnics, Issue 16, Winter, 17 (2002)
5) S. Gordon and B. J. McBride, NASA SP-273 (1976), NASA Lewis Research Center.
6) R. A. Sasse, Progress in Astronautics and Aeronautics, 109, 35−60 (1988).
7) R. Meyer, “Explosives”, Weinheim, New York, Verlag Chemie, 44 (1987).

揚薬としての黒色小粒火薬の燃焼性能

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本研究は黒色小粒火薬と黒色粉状火薬の燃焼温度を熱電対で測定し，燃焼火炎の伝播様子を高速度カメラで観察した。黒色小粒火薬が燃焼するとき，薬粒が燃焼火炎に巻き込まれ，燃焼ガスと一緒に流れながら，火炎の先端からやや遠くまで燃え続け，見かけの燃焼反応帯が広く，火炎の伝播速度が非常に速い。これに対して，密に充てんした黒色粉状火薬は燃焼波が平面状態を保ったまま平行に未燃焼火薬へ後退し，火炎の伝播速度が遅い。また，質量燃焼速度におよぼす雰囲気圧力や黒色小粒火薬の粒度の影響を検討した。

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