Research paper

Effect of firing current profile on the minimum ignition energy of an electric fusehead

Dongjoon Kim*† and Yozo Kakudate*

*National Institute of Advanced Industrial Science and Te chnology, 1−1−1 Higashi, Tsukuba, Ibaraki 305−8565, Japan
†Corresponding address : dj-kim@aist.go.jp

Received : November 16, 2011 Accepted : February 22, 2012

Abstract

In order to understand the condition of ignition of an electric fusehead, the effect of pulse height and duration of the firing current on the minimum ignition energy (MIE) has been investigated by experiments and numerical calculations. The experimental results show that MIE is strongly dependent on the height of the single square wave of the firing current. Numerical calculations were conducted to estimate the temperature distribution of the bridgewire considering an effect of heat losses from the bridgewire to the surroundings. As the results, it is found that the calculation can well reproduce the minimum time for ignition and MIE obtained by the experiment. In addition, the maximum temperature in the center of the bridgewire play an important role in determining ignition.

Keywords : electric fusehead, ignition energy, firing current, ignition temperature

1. Introduction

Recently an electric ignition system for launching fireworks has been spreading rapidly owing to the ease of time control and the operator safety by the remote control. In general many of igniters employ conventional batteries as a power source, and feed a current of the order of one ampere for several milliseconds to bridgewires of fuseheads in order to launch fireworks. Many studies on the ignition characteristics of the fusehead[1)−6)] have performed under the similar conditions. Our recent study[7)], however, of an ignition possibility of the fusehead caused by an induction current suggests that the minimum ignition energy (MIE) might be smaller than the nominal value, where the ignition energy is defined as an electric energy consumed in the bridgewire to ignite a explosive charge of the fusehead. The induction current may possibly happen to be produced by currents flowing adjacent firing cables when the many fireworks are launched simultaneously. Because the induced current is proportional to the time derivative of the adjacent current flows, it may reach several tens of amperes when the adjacent current is turned on or off, although its duration is very short, typically several tens of microseconds.

The difference of the duration of the firing current could affect the heat diffusion around the bridgewire, and therefore, MIE[1)]. In this study, the relationship between a profile of the firing current and MIE was investigated experimentally in detail as well as by numerical calculations of the heat diffusion.

2. Experimental

The structure of an electric fusehead is shown in Figure 1. The fusehead (Nippon Kayaku Co., Ltd) consists of a platinum−iridium alloy bridgewire of about 2.1 mm long and 0.03 mm in diameter, a pair of copper leg leads of 0.5 mm in diameter, and 25 mg of an explosive charge that is a1 : 1 mixture of lead thiocyanate ($Pb(SCN)_2$) and potassium chlorate ($KClO_3$). The resistance of the bridgewire is 0.6±0.05 Ω.

Figure 2 shows the electric circuit used to supply electric energy to the fusehead and to measure MIE. A d.c. power supply charges electrolytic capacitors connected in parallel to make a total capacitance 0.1 F. The capacitors are discharged through an electronic load (N3306A, Agilent Technologies, Inc.) that controls firing current flowing through the bridgewire to form a single square wave. Its time and current resolution is 0.05 ms and 0.01 A, respectively. The firing current is measured with a current probe (TCP312, Tektronix, Inc.) inserted into the circuit, and the voltage across the bridgewire is measured through the leg leads in the vicinity of the bridgewire, as

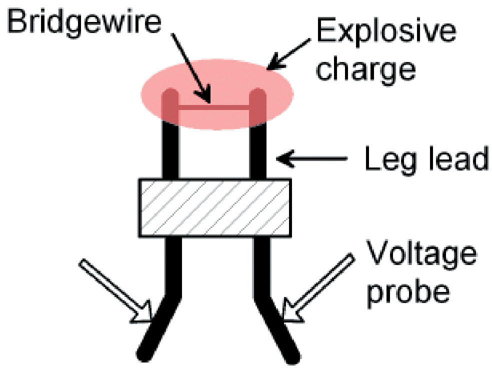

Figure 1 Structure of an electric fusehead.

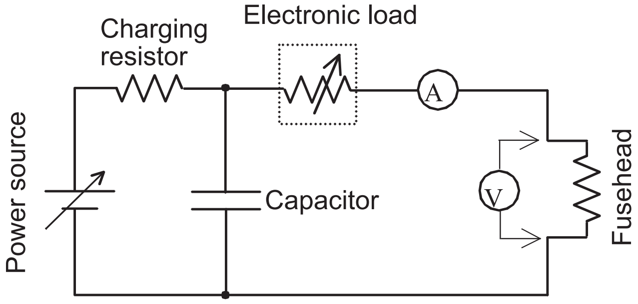

Figure 2 Electric circuit of the ignition equipment.

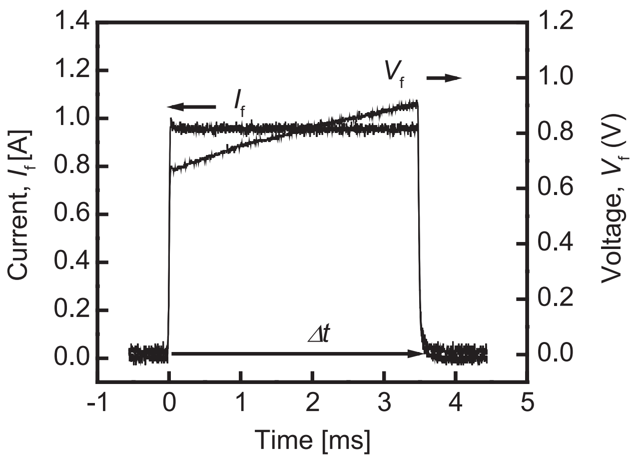

Figure 3 An example of time profile of firing current and voltage across the bridgewire.

shown in Figure 1, because the resistance of the leg leads is less than 0.5 % of that of the bridgewire.

Examples of the time profiles of the firing current (I_f) and the voltage across the bridgewire (V_f) are shown in Figure 3. The current is a well-defined single square wave with a duration time Δt and a pulse height I_{f0}. The reason V_f increases with time is that the bridgewire resistance increase, due to the temperature rise caused by the Joule heating. To determine MIE, the minimum duration time Δt_{min} needed to ignite the fusehead was obtained by varying Δt with 0.1 − 0.01 ms steps for a fixed I_{f0} and judging whether the fusehead ignited or not. Ignition of the fusehead can be easily confirmed by the sound of the explosion, the trace of reaction of the explosive, and the time profiles of the current and voltage.

3. Results and discussions

Figure 4 shows experimental results of the ignitability

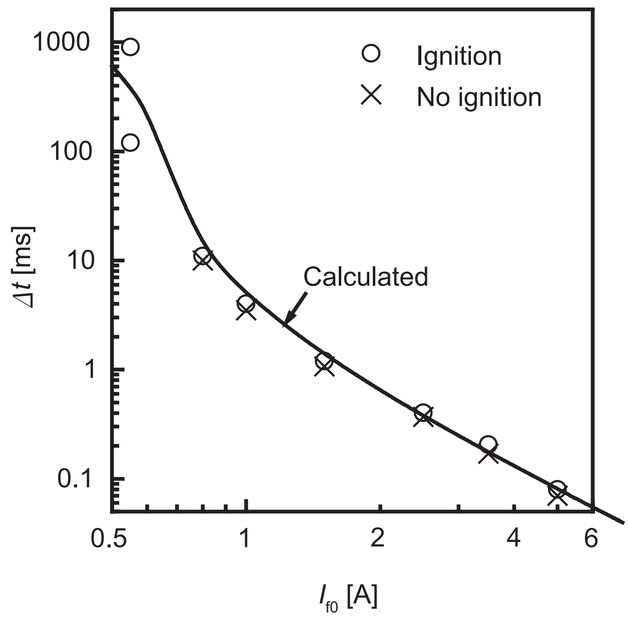

Figure 4 Effect of the pulse height of firing current (I_{f0}) and the duration time (Δt) on ignition of fusehead. A solid line indicates a calculated boundary for ignitability.

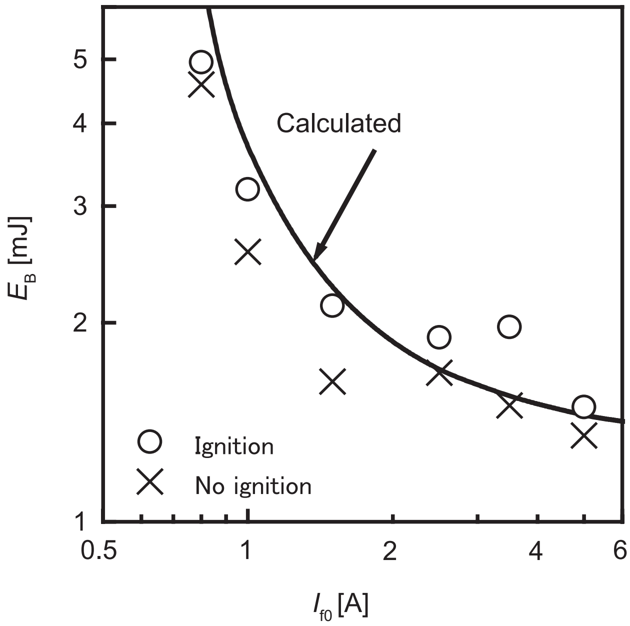

Figure 5 Effect of the pulse height of firing current (I_{f0}) and the electric energy consumed in bridgewire (E_B) on ignition of fusehead. A solid line indicates a calculated the minimum ignition energy (MIE).

dependence on I_{f0} and Δt. The circles and crosses in the figure denote that the fusehead ignited or not for a given I_{f0}, respectively. It is found that Δt_{min} increases with the decrease of I_{f0} from 5.00 to 0.55 A. When I_{f0} = 0.55 A, Δt_{min} varied widely in the range of 100−900 ms in each experiment, which shows that this current is very close to the threshold value that is the minimum current to get sufficient temperature to ignite the explosive against the heat diffusion. No ignition was observed in the case that I_{f0} was less than 0.50 A even though Δt was several seconds.

To estimate MIE, electric energy consumed in the bridgewire (E_B) was calculated by integrating the product

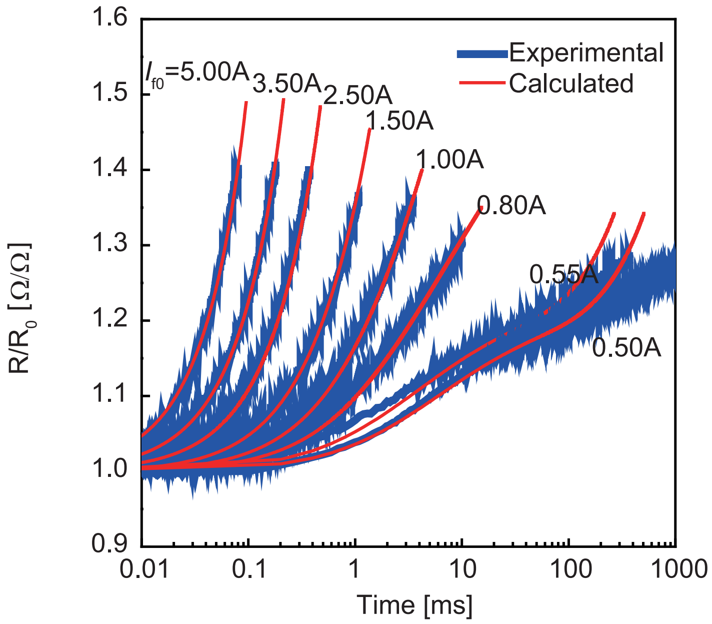

Figure 6 Time profiles of the resistance ratio (R/R_0) of the bridgewire for different pulse heights of firing current (I_{f0}).

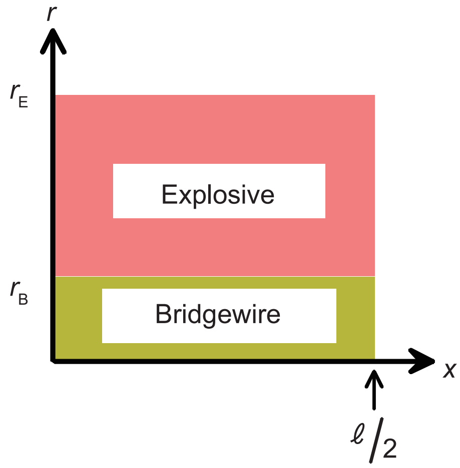

Figure 7 Calculation model for heat conduction.

Table 1 Physical properties of bridgewire and explosive charge

	Bridgewire	Explosive
Electric resistivity [Ω m]	2.60×10^{-7}	–
Density [kg m^{-3}]	2.1×10^{4}	174
Specific heat [J kg^{-1}K^{-1}]	130	720
Thermal conductivity [W m^{-1}K^{-1}]	27	0.8

I_fV_f with respect to time, and plotted as functions of I_{f0} in Figure 5. Although E_B at I_{f0} = 0.55 A is not shown in the figure, MIE values obtained were widely scattered in the range of 10–60 mJ. With increasing I_f, MIE decreases, that is, MIE is about 1.4 mJ when I_f = 5.0 A, and seemed to asymptotically approach 1.0 mJ or a somewhat larger value when I_{f0} was sufficiently large. This result seems to show the energy loss at the bridgewire cannot be ignored. The solid lines in Figures 4 and 5 show calculated boundaries for ignition with consideration of the heat diffusion, as discussed later.

In order to understand the reason why MIE depends on I_{f0}, the behavior of the bridgewire resistance was investigated in detail. Blue solid lines in Figure 6 show time profiles of the resistance ratio (R/R_0) for different I_{f0} when $\Delta t \approx \Delta t_{min}$, where R is the bridgewire resistance calculated by measured V_f and I_{f0}, and R_0 is R at room temperature. For convenience R/R_0 is plotted until the time when R/R_0 exhibits a discontinuous rise caused by abrupt temperature increase or the breaking of the bridgewire at the moment of ignition of the explosive. Because the resistivity of the platinum–iridium bridgewire changes almost linearly with temperature, it is considered that R/R_0 is approximately proportional to the average temperature of the bridgewire (T_{av}). There fore, it is interesting that T_{av} at the moment of ignition (T_{av0}) decreases with decreasing I_{f0}, because it is generally supposed that the temperature of the bridgewire is constant when the explosive ignites.

To clarify the reason for behaviours MIE and T_{av0}, the numerical calculations with a simple model were conducted taking into account of the temperature distribution of bridgewire caused by heat diffusion. The firing current causes Joule's heat to raise the temperature of the bridgewire, while the conduction of heat to the explosive charge and the leg leads reduces the temperature of the bridgewire. Figure 7 shows the simplified structure of the fusehead employed to calculate the temperature distribution. The length and radius of the bridgewire are represented by l and r_B, respectively, and the explosive surrounding the bridgewire has a cylindrical shape with radius r_E and the same height l, as the length of the bridgewire. Axes of coordinates are defined as shown in Figure 7; the plane of $x = 0$ is a plane of symmetry and the x–axis is an axis of symmetry. The boundary condition for the bridgewire at $x = l/2$ where the leg lead contacts is defined as a constant temperature and equals to the room temperature, because the copper leg lead is considered as a heat reservoir owing to its large heat capacity and large thermal conductivity compared with those of the Pt–Ir bridgewire. Heat transfers to the ambient air across the surfaces of the explosive at $x = l/2$ and at $r = r_E$, are considered as very small, so it is defined as zero. Actually, calculated results exhibited very slight temperature rises within the time we mainly concern. In order to accomplish the numerical calculations, the density, the thermal conductivity and the specific heat of each component of the fusehead are required. Some of them were measured in this study except for existing available data. The temperature dependence of electrical conductivity of Pt–Ir alloy was measured, and its thermal conductivity was estimated with the Wiedemann–Franz law. The density of the explosive was obtained by measuring its shape and weight. The specific heat of the explosive was measured by differential scanning calorimetry (DSC)[8]. The thermal conductivity of the explosive was estimated by measuring the temperature response of the surface of an explosive piece in which a heater was buried. The physical properties of the bridgewire and explosive are summarized in Table 1.

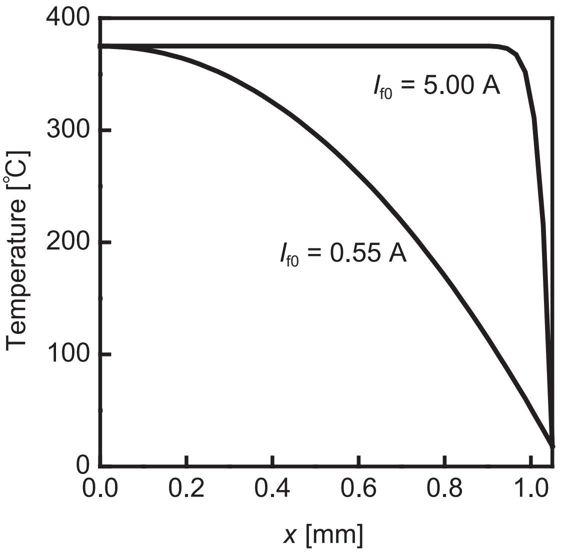

Figure 8 An example of calculated temperature distributions of the bridewire along its length (x) for different pulse heights of firing current (I_{f0}).

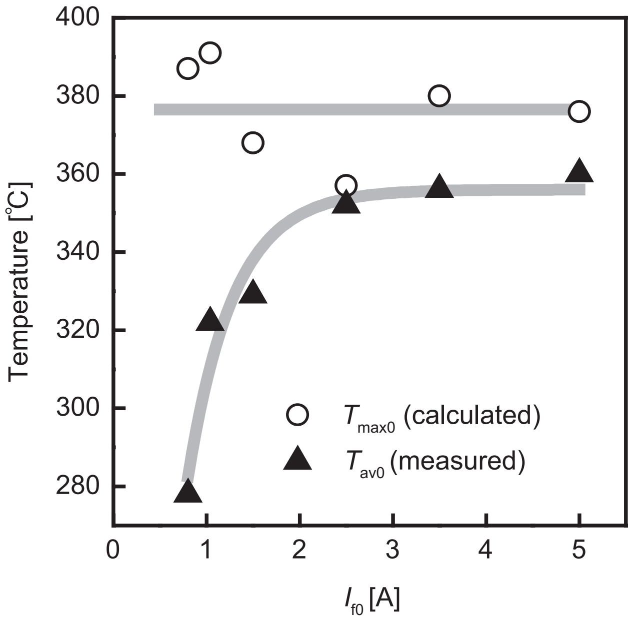

Figure 9 Dependences of average and center temperatures of the bridgewire at the moment of ignition on the pulse height of firing current (I_{f0}).

The calculated time dependences of R/R_0 for different I_{f0} are shown as red solid lines in Figure 6, and are good agreement with the experimental results, except for the region where the time is longer than about 100 ms, as observed for I_{f0} = 0.50A and 0.55A. This disagreement is considered to be caused by the heat transfer from the explosive to the ambient air after a long time, which is ignored in our simple calculation model.

Examples of calculated temperature distributions of the bridgewire along its length for I_{f0} = 5.00 A and 0.55 A are shown in Figure 8. The maximum temperatures (T_{max}) are observed in the center of the bridgewire (x = 0 mm). In these examples Δt are selected so that T_{max} coincide in both cases for convenience. In the case of large I_{f0} the temperature distribution is almost uniform, except in the vicinity of the contact point to the copper leg lead (x = 1.05 mm). But small I_{f0} induces the large temperature distribution, because Δt needed to reach the same T_{max} has to be long and the heat loss effect gets large. In this case, T_{av} is reduced even if T_{max} is equal to that for large I_{f0}.

As shown in Figure 9, T_{av0}, T_{av} at the moment of ignition, obtained from the experimental data shown in Figure 6 are plotted as the function of I_{f0}, as well as the calculated T_{max} at the same time (T_{max0}). When I_{f0} is large enough, T_{av0} seems to approach to T_{max0} asymptotically, while T_{av0} become smaller with decrea sing I_{f0} reflecting the heat loss effect. On the other hand the dependence of T_{max0} on I_{f0} seems to be small, nearly constant, which makes us suppose that T_{max0} is closely related to ignition of the explosive charge.

On the assumption that the explosive ignites when T_{max} reaches T_{max0} the averaged value of which is 375°C, the threshold values of Δt_{min} and E_B for ignitability were calculated. The results are indicated with full lines in Figures 4 and 5, and it is found that the results can well reproduce the experimental results.

However, results of the differential scanning calorimetry (DSC) measurements show that the ignition temperature of a mixture of lead thiocyanate and potassium chlorate is about 180°C. Therefore, there seems to be a discrepancy between these two results.

In case of the DSC measurement, an entire specimen is heated homogeneously, while only a very small volume of explosive charge is heated in case of ignition of the fusehead, because the ignition source is a very fine bridgewire. It is well known that the heat loss from the very small volume may exceed the heat generated by reaction in that volume, then it seems that it is not sufficient to bring the volume up to the ignition temperature. Therefore, temperatures of the bridgewire surface contacted with the explosive are required being well above the ignition temperature in order to initiate a chain branching reaction without quenching.

4. Conclusions

The minimum ignition energy (MIE) of an electric fusehead has been investigated by experiments and numerical calculations. The experimental results show that MIE is strongly dependent on the height of the single square wave of the firing current, that is, MIE decreased from 60 to 1.5 mJ with increasing a square pulse height of the current from 0.55 to 5.00 A. The numerical calculations were conducted with a simple model considering the effect of the conduction of heat from the bridgewire to the surroundings. The minimum time for ignition and MIE were calculated on the assumption that the explosive should ignite when the temperature in the center of the bridgewire reaches 375°C. The calculated results can well reproduce the experimental results.

References

1) E. Jones, Proceedings of the Royal Society of London, 198, 523 (1949).
2) K. Kato, Kogyo Kayaku (Sci. Tech. Energetic Materials), 20,

3
8
4

286 (1959).
3) Y. Nakano, Y. Tanaka, and T. Mizushima, Kogyo Kayaku (Sci. Tech. Energetic Materials), 26, 265 (1965).
4) Y. Mizushima and T. Sawada, Kogyo Kayaku (Sci. Tech. Energetic Materials), 27, 214 (1966).
5) R. Akiba and S. Kayuta, Kogyo Kayaku (Sci. Tech. Energetic Materials), 27, 349 (1966).
6) K. Sakamoto, Kogyo Kayaku (Sci. Tech. Energetic Materials), 36, 95 (1975).
7) D. Kim, S. Usuba, Y. Kakudate, and S. Fujiwara, Tenth international symposium on fireworks, pp. 61−70, Montreal (2007).
8) M. Akiyoshi, private communication.
9) K. Yamamoto, Kogyo Kayaku (Sci. Tech. Energetic Materials), 25, 134 (1964).