Ballistics of an Iron Bar Shot from a Mortar

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Abstract: *An accidental explosion in 1848 in the USA became a trigger for the development of neuroscience. An accidental explosion of black powder took place in a borehole for blasting and the expelled iron bar penetrated the head of a young man. He was injured but survived for 12 years. The authors were asked to calculate the speed, impact pressure or energy of the explosion by the producer of a TV program. At the time we were carrying out similar experiments using a mortar and firework stars, and so a model experiment was performed. Here we report of the results.*

Keywords: *black powder, ballistics, iron bar, shot energy efficiency*

Introduction

An accidental explosion involving black powder became a trigger for the development of neuroscience. On September 13, 1848, at a blasting site in Vermont, USA, Phineas Gage, a young man of 25 years old, was involved in an accident.[1] He accidentally dropped an iron tamping bar 6.1 kg in mass, 3.2 cm in diameter and 110 cm in length into a borehole 3.8 cm in diameter and 91 cm deep filled with about 0.4 kg black powder. An explosion took place, and the bar was shot from the borehole and penetrated his head from his left cheek to the top of his head. Amazingly he escaped death and survived for twelve years after the accident.

Twenty years after the accident, Gage's physician, John Harlow, perceptively correlated Gage's cognitive and behavioral changes with a presumed area of focal damage in the frontal region. His observation made considerable scientific impact and gave rise to controversy. Gage's skull was recovered and is in the Warren Anatomical Medical Museum at Harvard University.[2]

We were asked by the producer of a television program to calculate the velocity of the iron bar, the pressure of the bar on his brain, and the power of the explosion. In response to his request we carried out a small scale experiment using a mortar for firework star shots and a pressure measuring apparatus[3] and the results were analyzed as before.[4]

Experimental

Materials

The grain black powder and electric match were made by Nippon Kayaku Co. Ltd. This black powder may be similar to the black powder used in blasting 160 years ago in the USA. Howard[5] shows that the black powder manufacturing process has not changed in principle from *ca.* 1780 until now. Van Gelder and Schlatter[6] wrote in 1927 that blasting powder was made in very much the same way as gunpowder.

Apparatus

The iron bar is 1.5 kg in mass, 22 mm in diameter and 506 mm long. The mortar is shown in Figure 1. The inner diameter, wall thickness and depth of the mortar were 25 mm, 2.5 mm and 460 mm, respectively. The gap ratio in this case was 29%. The gap ratio GR (%) is defined as follows:

Here, S and s are the cross sectional areas of the

$$GR = \frac{S - s}{S} \times 100$$

mortar and the bar, respectively.

Two pressure sensors were fitted, to the bottom and to a position 300 mm from the bottom of the mortar. The mortar was fixed on an H-shaped steel holder as shown in Figure 2.

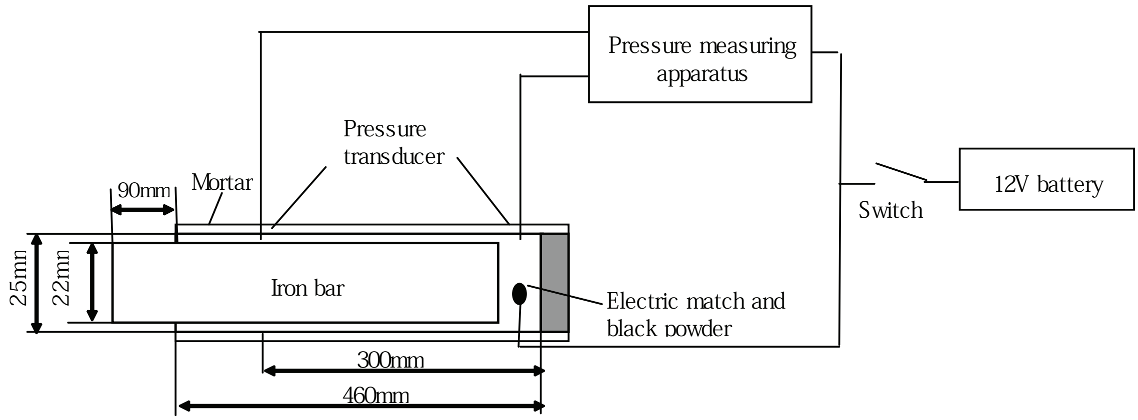

Figure 1 *Mortar and bar. The pressure in the mortar during the shot was measured and recorded using two pressure sensors (Kistler 60410A), charge amplifiers (Kistler 5011) and a digital oscilloscope (Sony Tektronix 5011).*

Procedure

The mortar was set on the ground vertically. The black powder and electric match were put in the bottom of the mortar. Then, a piece of tissue paper and the iron bar were inserted into the mortar slowly. The mortar fixed to the holder was set on the ground horizontally. The mortar was covered by U-shaped concrete blocks for safety. The space in front of the mortar was protected by sand bags and concrete blocks as shown in Figure 2.

The electric match was ignited by an electric current. The black powder burned, pressure developed and the bar moved forward. The pressure profile was recorded on an oscilloscope and the muzzle velocity of the bar was estimated from the pressure profile.

Results and Discussion

Pressure profile

An example of the observed pressure profiles in the mortar while the bar was shot is shown in Figure 3. The pressure profile shown by the fine line was recorded by the bottom sensor, and the profile shown by the thick line by the middle sensor. Both profiles in the figure were recorded simultaneously in the shot.

As indicated later, the bar stayed in the mortar while the pressure developed, that is, the combustion of the black powder had finished before the bar left the muzzle of the mortar. The pressure of the bottom sensor is higher than that of the middle sensor. The pressure of the bottom sensor is that in the space of the mortar behind the bar, and the pressure of the middle sensor is that in the gap

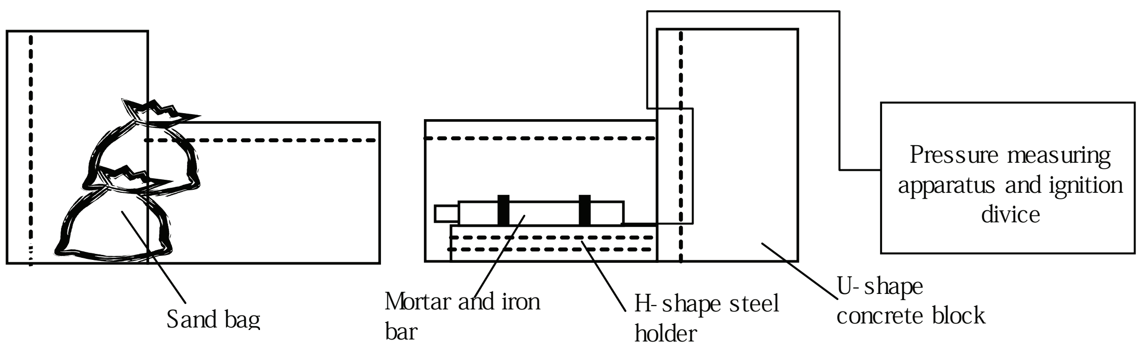

Figure 2 *Setup of the shot experiment of an iron bar.*

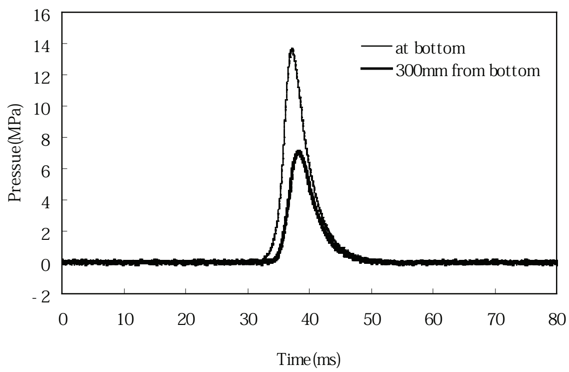

Figure 3 *Pressure profiles in the mortar with 7.5 g black powder.*

between the mortar wall and the bar.

Motion of a bar in the mortar

The motion equations of a bar in the mortar are expressed as follows:

$$m\frac{\mathrm{d}u}{\mathrm{d}t} = A \cdot p(t) \tag{1}$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = u \tag{2}$$

Here, m, u, A and z are the mass, velocity, cross sectional area and traveling distance of the bar, respectively.

$$A = \frac{\pi D^2}{4} \tag{3}$$

Here, D is the diameter of the bar, and

$$\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{\pi D^2}{4m} \cdot p(t) \tag{4}$$

Here, $p(t)$ is the observed value and is substituted into equation (4)

Equations (2) and (4) are simultaneously solved by numerical calculation, and acceleration du/dt, velocity u and traveling distance z are obtained.

Equations (2) and (4) were solved by the Runge–Kutta method. The time integration process for ordinary differential equations (2) and (4) was performed using a fourth order accuracy Runge–Kutta method.

The digital pressure data were recorded on an oscilloscope and the data were reduced using Excel. These reduced data were used for calculating acceleration, velocity and the distance traveled by the bar.

The calculated profiles of the acceleration, velocity and distance of the bar are shown in Figure 4.

In all cases, the velocity of the bar increased with time at first, then became constant, suggesting that the combustion of the black powder was complete and that the overpressure in the mortar reached zero. This situation can also be seen in time–distance curves in Figure 4. The distance of the bar from the bottom of the mortar increases with time, but at a point, the rate of increase changes, and then it becomes lower and constant. The change point occurs when the inner overpressure in the mortar reaches zero. With 10 g black powder, the inner overpressure reached zero just before the bar left the muzzle.

The observed and calculated results of the bar shot experiment are listed in Table 1.

Effect of mass of black powder on peak pressure and muzzle velocity

The effect of the mass of black powder on the peak pressures in the mortar is shown in Figure 5. The peak pressures at both the bottom and the middle of the mortar increased exponentially with the mass of black powder.

Plots of the calculated muzzle velocity and kinetic energy of the bar against the mass of black powder are shown in Figure 6. The calculated muzzle velocity increased linearly with the mass of black powder (BP), but the calculated kinetic energy showed an exponential increase with the mass of BP.

Energy efficiency of the shot of the iron bar, shell and star from mortar

It is necessary to know the energy efficiency of the shot of the iron bar from the borehole in Gage's case, in order to estimate the initial velocity and kinetic energy of the bar. The shot energy efficiency of the iron bar, shell and star which were observed

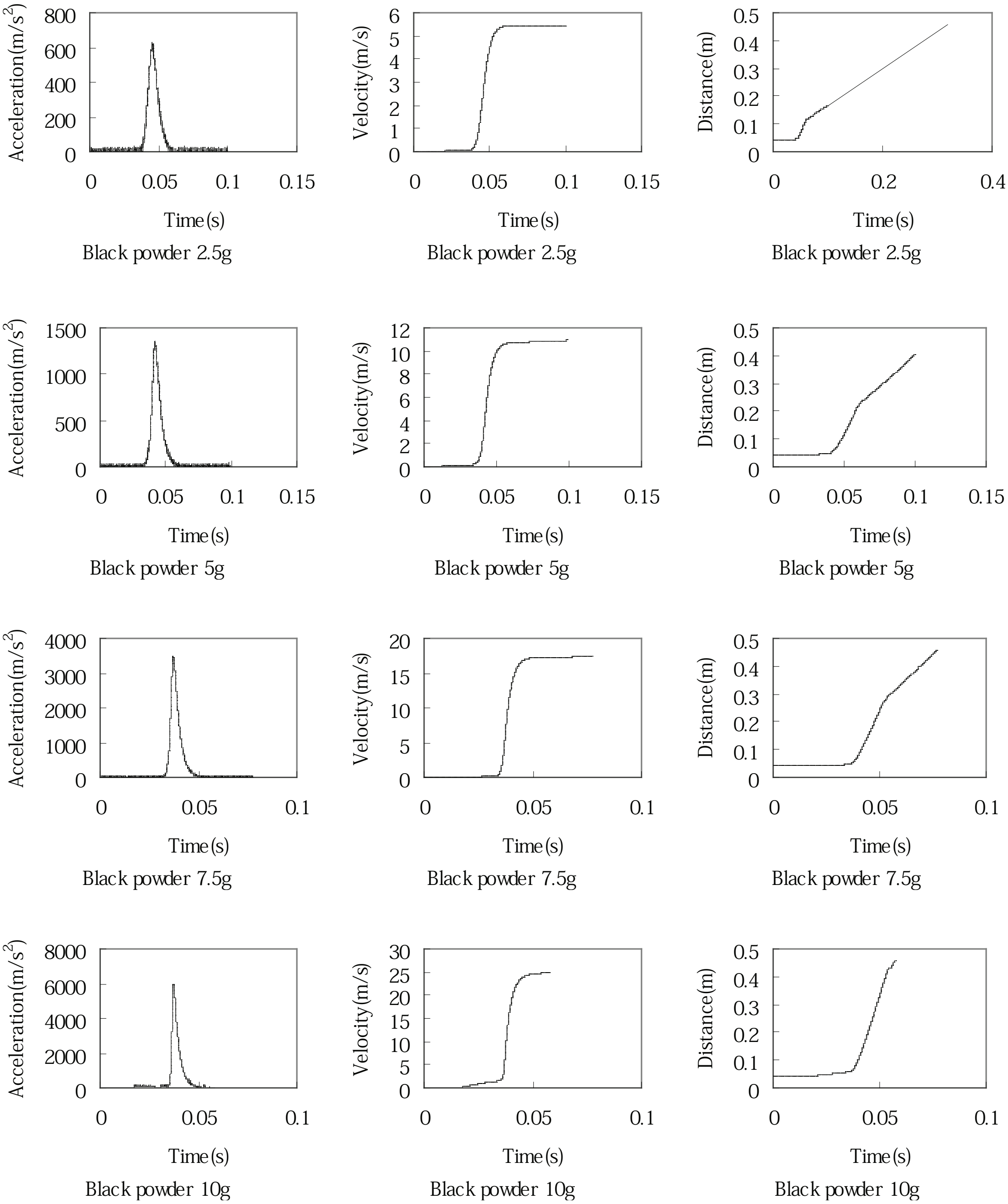

Figure 4 *Calculated profiles of the velocity and distance of the bar in the mortar.*

in experiments are listed in Tables 1 and 2. The shot energy efficiency in Tables 1 and 2 is the kinetic energy of the shot of a projectile divided by the explosion energy of black powder. The explosion energy of black powder was measured and published as 2800 J g^{-1} by Rose.[7]

We could not perform the experiment on the same scale as Gage's case, because no safe facility was available for the experiment. The information from this experiment was limited so it was necessary to estimate the data in Gage's case. So we used for a supplement the star and shell data which we had previously obtained.[4,8]

A plot of the shot energy efficiency of the iron bar against the mass of BP in this work is shown in Figure 7. In this case, with 23% GR, the shot

Table 1 *Observed and calculated results (GR = 23%).*

Run	Mass of BP (g)	P_{max1} (MPa)	T_{max1} (ms)	P_{max2} (MPa)	T_{max2} (ms)	ΔT (ms)	CMV (m s^{-1})	KE (J)	EE (%)
1	15	—	—	—	—	—	—	—	—
2	10	23.3	2.88	11.86	4.06	18.53	24.8	460	1.64
3	7.5	13.55	5.54	6.94	6.86	20.84	17.4	227	1.08
4	5	5.42	7.86	2.77	8.74	24.1	10.9	89	0.64
5	2.5	2.4	9.22	1.16	10.73	25.66	5.4	22	0.31

BP: black powder; P_{max1}: maximum pressure by the bottom pressure transducer; P_{max2}: maximum pressure by the middle pressure transducer; T_{max}: time to maximum pressure: ΔT: time during positive overpressure; CMV: calculated muzzle velocity; KE: kinetic energy of the bar; EE: energy efficiency of the shot

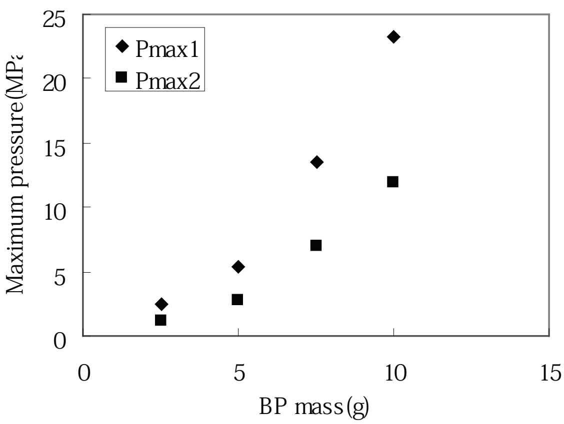

Figure 5 *Plot of peak pressures in the mortar against the mass of black powder.*

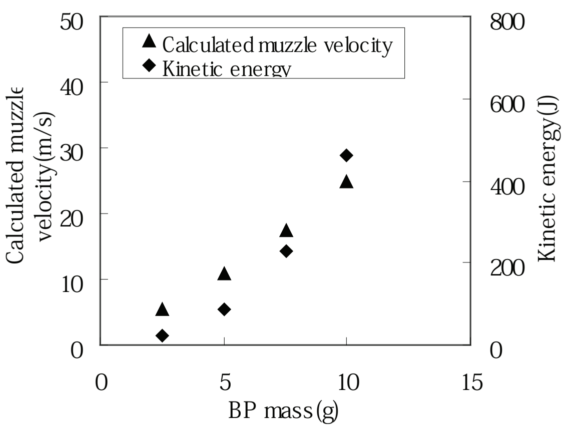

Figure 6 *Plots of the calculated muzzle velocity and kinetic energy of a bar.*

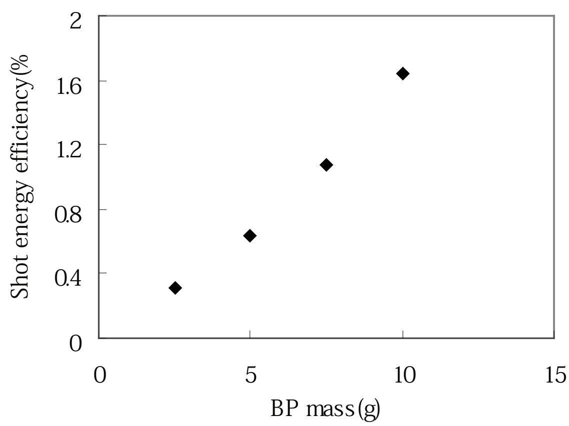

Figure 7 *Plot of the shot energy efficiency of an iron bar vs. BP mass with 23% GR.*

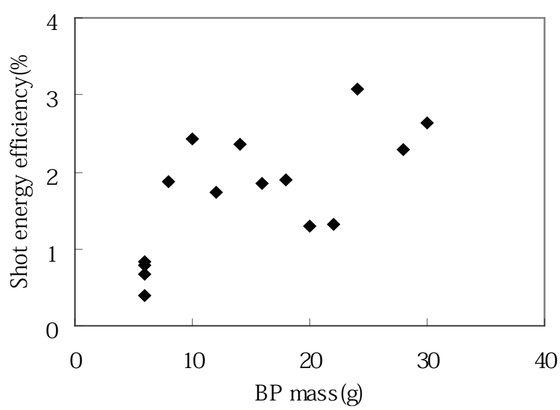

Figure 8 *Plot of the shot energy efficiency of a no. 3 firework shell vs. BP mass with about 13% GR.*

Table 2 *Shot energy efficiency of iron bar, shell and star.*

(1) No. 3 Shell. Dimensions of mortar: ∅ 90 mm × 750 mm (Ref. 4,9)

Run	BP mass (g)	Shell mass (kg)	Shell diameter (m)	GR (%)	Muzzle velocity (m s^{-1})	KE (J)	EE (%)
1	30	0.242	0.084	13	135	2208	2.63
2	28	0.242	0.084	12	122	1797	2.29
3	24	0.237	0.084	13	132	2061	3.07
4	22	0.240	0.084	12	82	807	1.31
5	20	0.240	0.084	14	78	730	1.30
6	18	0.242	0.084	13	89	958	1.90
7	16	0.242	0.084	13	83	834	1.86
8	14	0.239	0.084	14	88	926	2.36
9	12	0.237	0.084	14	70	581	1.73
10	10	0.255	0.083	15	73	679	2.43
11	8	0.258	0.083	15	57	419	1.87
12	6	0.250	0.083	15	30	113	0.67
13	6	0.250	0.083	15	23	66	0.39
14	6	0.241	0.084	13	33	131	0.78
15	6	0.241	0.083	15	34	139	0.83

(2) Star. Dimensions of mortar: ∅ 25 mm × 460 mm (Ref. 8)

Run	BP mass (g)	Star mass (kg)	Star diameter (m)	GR (%)	Muzzle velocity (m/s)	KE (J)	EE (%)
1	1	0.0095	0.0224	20	87	36	1.29
2	0.4	0.0095	0.0227	18	27	3	0.31
3	0.7	0.0091	0.0223	20	57	15	0.75
4	2	0.0092	0.0222	21	117	63	1.13
5	1.5	0.0083	0.0218	24	103	44	1.05
6	1.5	0.0089	0.0224	20	106	50	1.19
7	2	0.0086	0.0225	19	117	59	1.05
8	1.5	0.0088	0.0226	18	86	33	0.78
9	1.25	0.0083	0.0224	20	77	25	0.70
10	1.75	0.0085	0.0220	22	91	35	0.72

energy efficiency increased linearly with mass of BP.

A plot of the shot energy efficiency of a no. 3 firework shell against BP mass is shown in Figure 8. The shot efficiency increased with BP mass, though the observed data are very scattered.

Figure 9 shows a plot of the shot energy efficiency of firework stars. With about 20% GR, the shot energy efficiency increased with BP mass in the range of 0–2 g BP. But with about 30% GR, the efficiency decreased somewhat with increasing BP mass when the BP mass exceeded 2 g.

Figure 10 shows a plot of the shot energy efficiency of stars *vs*. GR with 2 g BP mass. The efficiency

Table 2 continued *Shot energy efficiency of iron bar, shell and star.*

(3) Star. Dimensions of mortar: ∅ 20 mm × 360 mm (Ref. 8)

Run	BP mass (g)	Star mass (kg)	Star diameter (m)	GR (%)	Muzzle velocity (m s^{-1})	KE (J)	EE (%)
1	1	0.0038	0.0167	30	79	12	0.42
2	2	0.0038	0.0172	26	116	25	0.45
3	3	0.0037	0.0169	28	131	32	0.38
4	4	0.0041	0.0174	24	167	57	0.51
5	5	0.0033	0.0166	31	145	35	0.25
6	6	0.0038	0.0167	31	190	69	0.41
7	7	0.0037	0.0171	27	195	70	0.36
8	2	0.0039	0.0171	27	119	28	0.49
9	2	0.0040	0.0175	23	138	38	0.68
10	2	0.0035	0.0162	35	134	32	0.57
11	2	0.0041	0.0175	24	121	30	0.53
12	2	0.0038	0.0167	30	126	30	0.54
13	2	0.0019	0.0134	55	93	8	0.15
14	2	0.0018	0.0133	56	83	6	0.11
15	2	0.0018	0.0132	57	104	10	0.18
16	2	0.0020	0.0138	52	104	11	0.19
17	2	0.0018	0.0132	57	90	7	0.13
18	2	0.0009	0.0103	73	65	2	0.03
19	2	0.0008	0.0105	72	40	1	0.01
20	2	0.0009	0.0104	73	39	1	0.01
21	2	0.0011	0.0111	69	90	4	0.08
22	2	0.0010	0.0110	70	79	3	0.06

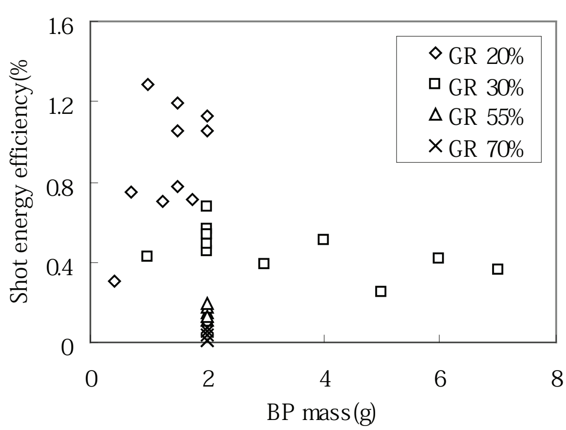

Figure 9 *Plot of the shot energy efficiency of firework stars vs. BP mass with various GR.*

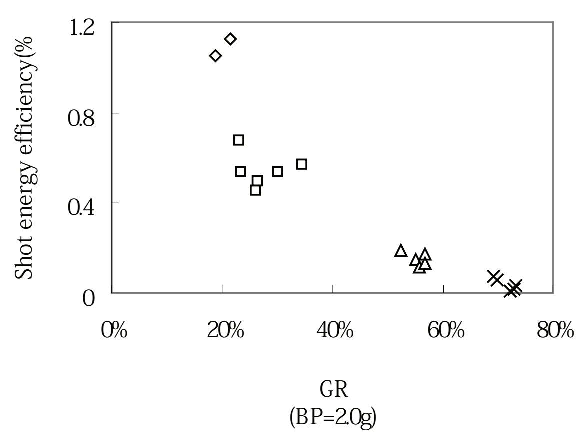

Figure 10 *Plot of the shot energy efficiency of firework stars vs. GR with 2 g BP mass.*

Table 3 *The maximum shot energy efficiency of iron bars, no. 3 firework shell and stars.*

	Shell	Star	Star	Bar (this work)	Bar (Gage's case)
Projectile mass (kg)	0.24	0.0038	0.0038	1.5	6.1
BP mass (kg)	0.024	0.0020	0.0060	0.010	0.40
Projectile/BP	10	1.9	0.63	150	15
GR (%)	13	30	31	23	29
Shot energy efficiency (%)	3.1	0.54*	0.41**	1.6	?

*Maximum shot energy efficiency with 2.0 g BP mass. **Not maximum shot energy efficiency with 6.0 g BP mass.

decreases with increasing gap ratio.

The information about the maximum shot energy efficiencies of iron bars, no. 3 shells and various stars are listed in Table 3. In this Table, the maximum shot energy efficiency was obtained with a small gap ratio (13–20%) and the largest BP mass in the experimental range. However, with a larger gap ratio (about 30%), the efficiency decreased with increasing BP mass (< 2 g).

Estimation of the velocity and kinetic energy of the iron bar in Gage's case

At the moment it is difficult to estimate the shot energy efficiency in Gage's case accurately. Most of data showed that the efficiency increased with BP mass in the experimental range. But with about 30% gap ratio the efficiency decreased with BP mass when the mass exceeded a critical value. From above considerations, the shot energy efficiency of the iron bar in Gage's case may be roughly estimated at about 1%.

The kinetic energy and muzzle velocity of the iron bar in Gage's case are estimated to have been about 11 kJ and 60 $m\ s^{-1}$, respectively. A more reliable estimation may be obtained by conducting a similar experiment using the same experimental conditions as in Gage's case.

In our experiment with 15 g black powder, the expelled iron bar penetrated a 20 cm long sand bag and then made a hole in a concrete board about 5 cm thick.

According to the Department of Defense, USA,[10] a hazardous fragment is one having an impact energy of 79 J or greater. The energy of the expelled bar in Gage's case was much greater than the energy of a hazardous fragment.

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