Mechatronis: The Output Energy of MEMS Explosive Train

Ming Tan¹, Liang Zhang²⁺, Xiangtao Zeng³ and Wen Xia⁴

¹Sichuan Huachuan Industries Co., Ltd, Chengdu, China
²School of Electronics Engineering and Computer Science, Peking University, Beijing, China
³Special Energy Group Xian Qinghua Co., Xi’an, China
⁴China Xi’an Satellite Control Center, Xi’an, China

*Corresponding author: 1806389278@pku.edu.cn

Abstract. A micron scale of microelectromechanical systems (MEMS) explosive train with applications in both space exploration and electronic control of safety airbag, the MEMS explosive train is designed to shock initiate a linear shaped charge by accelerating a thin metal plate across a small gap. This paper summarizes the experiment results of Φ0.9×0.6mm micro-charge driven different thickness flyer’s velocity by Photonic Doppler Velocimetry (PDV), compared to the calculation result of Gurney formulation, the flyer’s velocity of micro-charge driven different thickness lower than the calculation. The velocity-time variation curve and the energy variation with distance provide some information available for micro-explosive train design.

Keywords: MEMS, micro-charge, flyer, PDV, energy.

1. Introduction
The rapid development of the MEMS safety and arming devices make multiple devices and systems size is reduced, the efficiency is greatly increased. As a kind of MEMS Pyrotechnics, The scale of its key device is in the sub millimeter scale, the system scale is in millimeter [1]. Gerald Laib assembled copper azide (mass of 10mg) by in situ charge technology into miniature safety insurance institutions with the cross section size in 0.1~1mm, as the key device of MEMS safety device, the flyer with special structure sheared by the charge can get more than 100mJ of the flyer kinetic energy under less than 1mJ of the input energy [2]; Rui Zhen Xie sheared 0.02mm titanium flyer impact detonated CL-20 by in situ charge copper azide (mass of 0.47mg), but failed to initiation [3]. Copper azide’s electrostatic sensitivity is extremely high, which influences it being used widely in explosive train. Meanwhile, lead azide in micro scale also has a good deflagration to detonation transition performance [4]. To further increase the safety of micro-charge driven flyer, this paper designed the structure of lead azide charge driven titanium flyer and used PDV velocity measurement technology to preliminary research for the output energy from micro-charge driven different thickness titanium flyer.
2. Experiment preparation and estimation

2.1. Materials selection

Micro charge: lead azide is an explosive salt of hydrazoic acid, when its charge diameter was 0.9mm, the charge density was 80% of the TMD, and the critical height of the detonation growth was about 1.8mm. At a charge height greater than 2.4mm, the detonation wave was stable with a detonation pressure of 6.0GPa [4]. So, it has a good deflagration to detonation transition performance in micro scale.

Flyer: under the same conditions, the detonation performance of the output flyer is compared. The initiation ability of 0.1mm titanium is much stronger than 0.1mm steel, 0.2mm aluminum [5]. Meanwhile the effective charge is the sub milligram, select 0.02mm titanium to verify the feasibility of micro-charge drive flyer, furthermore, compare to Ruizhen Xie’s result.

Figure 1. Micro-charge and mould figure.

2.2. Measurement preparation

The assembly structure of micro charge driven flyer is shown in Figure 2.

Figure 2. Micro-charge driven flyer Schematic and assembly structure figure.

Photonic Doppler Velocimetry (PDV) is novel of laser velocimetry system. It is widely used in the velocity measurement of the shock wave, detonation wave and short-time high-velocity moving objects. It can record the velocity and time at the same time by fast Fourier transform.
2.3. Estimation of flyer velocity by Gurney formulation

Before the test, the velocity of flyer is deduced from the classic Gurney formulation. As the charge mode is the cylinder charge, the flying speed formulation is:

\[ V_f = \sqrt{\frac{2E_g}{m_m + \frac{1}{2}m_c}} \]  

(1)

Where the \( V_f \) is the flyer velocity; \( m_m \) is flyer mass; \( m_c \) is the charge mass; \( E_g \) is the charge Gurney energy. The Gurney energy of lead azide can be calculated by estimation method of Shenyang, Wang Hui [6]:

\[ \sqrt{2E_g} \approx D \sqrt{\frac{2}{\gamma^2-1}\left(\frac{\gamma}{\gamma+1}\right)^\gamma} \]

\[ \gamma = \rho_0/ (0.14+0.26\rho_0) \]  

(2)

Where \( \gamma \) is polytropic index, \( \rho_0 \) is charge density; \( D \) is the charge detonation velocity.

The error of the calculated value and the actual value, which resulted from radial loss, are rectified by the reduced angle [7], as shown in figure 3.

![Figure 3. Cylinder charge under radial loss [7].](image)

When the charge diameter \( d \) is larger than the charge height \( h \), the effective charge mass \( m_e \) is equal to the mass of cone shape charge outside the angle theta, the expression is:

\[ m_e = \rho_c\left(\frac{3}{4}d^2 - \frac{3}{2}dhtg\theta + h^2tg^2\theta\right)\frac{\pi h}{3} \]  

(3)

Where \( \rho_c \) is charge density. Under the charge density of 3.9g/cm\(^3\), the effective charge of \( \Phi 0.9\times0.6mm \) is 0.71mg. After angle rectify of the Gurney formulation, the 0.02mm titanium flyer calculation velocity is 1973m/s, the 0.1mm titanium flyer calculation velocity is 1752m/s.

3. Experimental Result and Analysis

3.1. Experimental Result

By the PDV test system, the micro-charge driven 0.02mm thickness titanium flyer velocity curve is shown in figure 4.
Figure 4. Micro-charge driven 0.02mm flyer velocity-time curve.

From Figure 4, flyer velocity is growing before 2.2μs, the maximum velocity is about 1956m/s, the duration of the flyer velocity is about 1.6μs within 95% of the maximum velocity. By integral calculation, the distance of flyer is 0.34mm in 1μs, and 2.57mm in 2.2μs, the flyer velocity reached maximum value in this range. By difference calculation, obtain the acceleration change process of flyer, and then deduced the force change process of flyer. The maximum force on the flyer is 1.31N at 0.78μs. Through time travel and energy curve found that energy reach the maximum value 50MJ at the 2.22μs when the distance of flyer was 2.57mm.

By the PDV test system, the micro-charge driven 0.02mm thickness titanium flyer velocity curve is shown in figure 5.

Figure 5. Micro-charge driven 0.1mm flyer velocity-time curve.

From Figure 5, flyer velocity is growing before 3.5μs, the maximum velocity is about 1571m/s, the duration of the flyer velocity is about 1.0μs within 95% of the maximum velocity. By integral calculation, the distance of flyer is 0.46mm in 1μs, and 2.99mm in 3.5μs, the flyer velocity reached maximum value in this range. By difference calculation, obtain the acceleration change process of flyer, and then deduced the force change process of flyer. The maximum force on the flyer is 0.22N at
1.0μs. Through time travel and energy curve found that energy reach the maximum value 158mJ at the 3.5μs when the distance of flyer was 2.99mm.

3.2. Analysis
Details of the velocity and time of micro charge driven different thickness flyer are shown in table 1.

| Parameter                                | 0.1mm flyer | 0.02mm flyer |
|-------------------------------------------|-------------|-------------|
| Calculation velocity Vf (m/s)             | 1752        | 1973        |
| Measured velocity V (m/s)                 | 1571        | 1956        |
| Velocity loss (%)                         | 10.3        | 0.8         |
| velocity increased time (μs)              | 3.5         | 2.2         |
| distance of maximum velocity (mm)         | 2.99        | 2.57        |
| maximum kinetic (mJ)                      | 158         | 50          |

Note: velocity loss is mean $$\frac{V_f - V}{V_f} \times 100\%$$.

In Table 1, it can be found that the measured velocity of titanium flyer is smaller than the calculated value by Gurney formulation, indicating that the consumed energy of the micro charge shear flyer cannot be ignored, the measured velocity of shearing 0.1mm titanium flyer occupies 10.3% of the calculation flyer velocity; the measured velocity of shearing 0.02mm titanium flyer occupies 0.8% of the calculation flyer velocity. The greater the thickness of the flyer, the larger proportion of the energy of shearing flies plate.

The flyer velocity can achieved 1900m/s, and the flyer kinetic can achieved 158mJ, meanwhile, flyer kinetic energies less than 100mJ are adequate to initiate explosives such as HNS-IV (250μm spot size) [2]. Therefore, micro-charge driven flyer can initiate HNS-IV in theory.

By collecting and observing the flyer plates, it is found that there are two kinds of shapes, which are circular shape and pellet shape. As shown in figure 6.

Figure 6. Flyer figures of circular shape (L) and pellet shape (R).

4. Conclusions
Experiments demonstrated that micro-charge driven flyer can be achieved in milligram charge level, which can make the flyer velocity of 0.02mm titanium above 1900m/s and 0.1mm titanium flyer above 1500m/s.

Micro-charge driven 0.1mm titanium flyer’s kinetic is 158mJ which is above 100mJ, which can initiate HNS-IV boosters in theory. The distance where flyer kinetic is maximum is about 2.57~2.99mm, this result can help design micro explosive train.

References
[1] Chu Enyi, He Aifeng, Ren Xi, Pyrotechnics integration technology development opportunities
and ways [J]. Chinese journal of energetic materials, 2015, 23 (3): pp205-207.

[2] Gerald Laib, Integrated thin film explosive micro-detonator [P] US007497164B1, 2009, 3, 3.

[3] Ruizhen Xie, Liu Lan, Ren Xiao-ming, Research on In-situ Charge and Performance of Si-based Micro-detonator [J]. Acta Armamentatii, 2014, 35 (12): pp1973-1977.

[4] Nan Yan; Ai-Jun He; Wan-Jun Geng. Research on Detonation Growth of Lead Azide (Pb(N3)2) Microcharge [J]. Chinese journal of energetic materials, 2013, pp156-163.

[5] Kaimin Wang, Research on explosive train [D]. Beijing, Beijing Institution of Technology, 2002.

[6] Fei Shen, Hui Wang, Jianfei Yuan. A simple method to estimate coefficients of explosive Gurney [J]. Journal of Explosives & Propellants, 2013, 36 (6): pp36-38.

[7] Xiufeng Han, Study on energy transfer mechanism between elements of explosive train [D]. Beijing, Beijing Institution of Technology, 2004.