Propellants, Explosives, Pyrotechnics

DOI: 10.1002/prep.201300108

Parametric Influences on the Sensitivity of Exploding Foil Initiators

Qing-Chou Chen,[a, b] Qiu-Bo Fu,[b] Lang Chen,*[a] and Zhong-Fei Han[a]

Abstract: Analyses of firings by the up-and-down method were employed to gain a better understanding of the influences of foil bridge width, foil thickness, flyer thickness, and barrel length on the sensitivity of exploding foil initiators. Characterization was performed via the mean threshold voltage. The results showed that the mean threshold voltage of exploding foil initiators was reduced by 16% when the foil bridge width was reduced from 0.4 mm to 0.3 mm, which means that a reduced foil bridge width could decrease the mean threshold voltage of exploding foil initiators as suggested by theoretical analysis. The mean threshold voltage of exploding foil initiators was reduced by 20% as the flyer thickness was decreased from 50 μm to 25 μm, which could be an efficient way to improve the sensitivity of exploding foil initiators. The flyer accelerated to over 90% maximum velocity after flying 0.15 mm in a fine barrel, which revealed that exceeding a barrel length of 0.15 mm has little effect on the performance of exploding foil initiators.

Keywords: Explosive mechanics · Sensitivity · Exploding foil initiators · Metal foil

1 Introduction

Exploding foil initiators are third generation pyrotechnic devices with improved safety because they consist of a secondary explosive with high density instead of a primary explosive. There is no direct contact between energy transformer and explosive and they are initiated by a specific electrical pulse. Exploding foil initiators and their function are best described by the following scheme: substrate, metal foil bridge, flyer, barrel, acceptor explosive pellet. This is also illustrated in Figure 1.

A capacitor bank is discharged through the thin metal foil bridge resulting in its fast vaporization. This phenomenon, which is called burst of the foil bridge, occurs with a sharp maximum foil resistance and abrupt electrical power input. The plastic flyer is sheared at the inner radius of the barrel and the thus formed flyer disk is subsequently accelerated by high pressure vapor. Flyer velocities as high as 3000 m s^{-1} could be achieved in this way. Exploding foil initiators are widely used in ballistic missile systems, aerial defence systems, air-to-air missile systems, and anti-tank missile systems. They are also are suitable for other weapon systems.

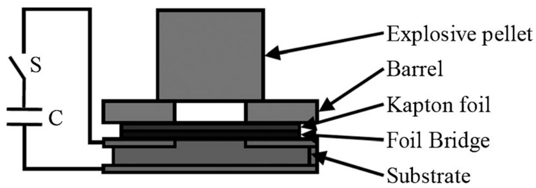

Figure 1. Schematic depiction of the exploding foil initiator.

Miniaturization and low energy initiation are two of the promising trends in the development of exploding foil initiators [1]. For that purpose, investigations on the sensitivity of exploding foil initiators were performed. The effect of exploding foil size on the flyer velocity was investigated [2], and the results revealed that the flyer velocity reaches a maximum at an exploding foil thickness of 3.67 μm. Additionally, a smaller foil thickness could enlarge the flyer velocity and could lead to a decrease in the initiation energy of exploding foil initiators. The influence of foil thickness on the sensitivity of exploding foil initiators was investigated [3]. The results suggested that reducing the thickness of the metal foil bridge would decrease the initiation energy of exploding foil initiators. Both papers only focused on the thickness of the metal foil bridge and did not consider the other factors. The effects of the thickness of the metal foil bridge, the flyer thickness, and the barrel length on the sensitivity of exploding foil initiators were investigated [4]. The results showed that decreasing thickness of foil and flyer reduced the mean threshold voltage. However, a barrel length in the range of ca. 0.125–0.225 mm has little

[a] Q.-C. Chen, L. Chen, Z.-F. Han
School of Mechatronical Engineering
Beijing Institute of Technology
100081, Beijing, P. R. China
*e-mail: chenlang@bit.edu.cn

[b] Q.-C. Chen, Q.-B. Fu
Institute of Chemical Materials
China Academy of Engineering Physics
621900, Mianyang Sichuan Province, P. R. China

Table 1. Results of the up-and-down test.

No.	Foil width [mm]	Foil thickness [μm]	Barrel length [mm]	Flyer thickness [μm]	Mean threshold voltage [V]
1	0.4	4	0.4	50	2110
2	0.3	4	0.4	50	1770
3	0.3	4	0.4	25	1440
4	0.3	4	0.2	25	1995
5	0.3	3	0.2	25	1750
6	0.3	3	0.4	25	2135

influence on the sensitivity of exploding foil initiators, which means that the flyer has been fully accelerated to peak velocity.

In this paper, the effects of metal foil bridge width, foil thickness, flyer thickness, and barrel length on the sensitivity of exploding foil initiators are investigated. The results are compared with the literature to get a better insight in the detailed mechanisms. It was aimed to optimize the initiation energy of exploding foil initiators.

2 Experimental Techniques

Copper foil bridges were magnetron sputtered onto a porcelain temper. The deposition was performed in an evacuated chamber pumped to a base pressure of 10^{-4} to 10^{-5} Pa. The atmosphere of the chamber was filled with argon to initiate the sputtering process. Atoms were sputtered from the pure copper target (99.99%). The rotating substrate, which takes up the plasma resulting in forming layer-structured films, was positioned directly above the magnetron sources. Foils of three different sizes were made by the magnetron sputter deposition system. They have a square shape as illustrated in Figure 2.

The sizes (width × thickness) of the metal foil bridges are 0.3 mm × 3 μm, 0.3 mm × 4 μm, and 0.4 mm × 4 μm, respectively. Barrels are manufactured from steel and have a length of 0.2 mm or 0.4 mm. Flyers are made from Kapton polyimide film and have a thickness of 25 μm or 50 μm. The pellets are made from HNS-IV explosive pressed to 90%TMD density. The up-and-down method was employed to evaluate the sensitivity of exploding foil initiators, which was characterized by a mean threshold voltage.

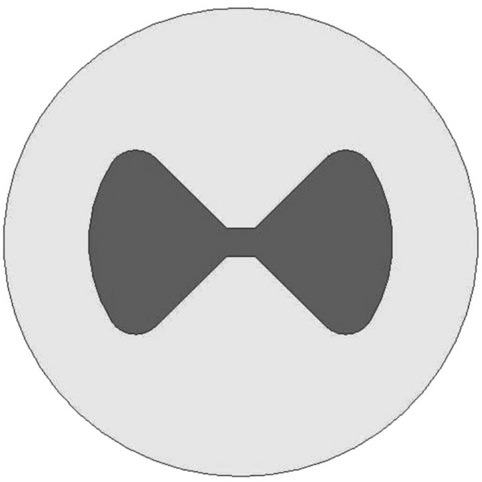

Figure 2. Schematic diagram of the foil bridge shape.

Exploding foil initiators assembled from different sized metal foil bridges, flyers and barrels were tested. All tests were separated into two groups, which slightly differed in the initiation conditions. The effects of metal foil bridge width and flyer thickness on the sensitivity of exploding foil initiators were investigated in the first group; whereas the effects of foil thickness and barrel length on the sensitivity were investigated in the second group. As the up-and-down tests required a large number of firings to get sufficient data, only two sample points were carried out at each firing condition. To minimize the number of tests and to maintain the efficiency of test data, the experimental data is compared with that obtained from literature. The results of the up-and-down tests are listed in Table 1.

3 Results and Discussion

3.1 Influence of the Foil Bridge Width on the Sensitivity of Exploding Foil Initiators

Exploding foil initiators with 0.3 mm (test No. 2) and 0.4 mm (test No. 1) foil bridge width, which have similar foil thickness, flyer thickness, and barrel length, were tested by the up-and-down method. The test results are illustrated in Figure 3, which shows that the mean threshold voltage of the exploding foil initiators with 0.4 mm foil bridge width is 2110 V, whereas that of 0.3 mm is 1770 V. The voltage is reduced by about 16% as the foil bridge width decreases from 0.4 mm to 0.3 mm.

A method to characterize the critical energy for short duration initiation of heterogeneous high-energy explosives ($p^2\tau$ = constant) was introduced by Walker et al. [5], which also is suitable to elucidate the initiation process of exploding foil initiators. The initiation of explosive depends on pressure (p) and its duration (τ). Given that the materials of explosive and flyer are fixed, the pressure mainly depends on the flyer velocity. The duration, however, depends on the flyer thickness. With similar foil bridge materials and flyer parameters, the initiation of exploding foil initiators only depends on the flyer velocity, which could be calculat-

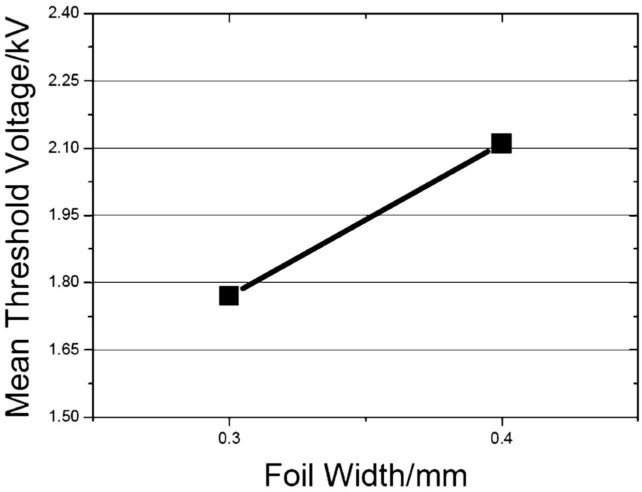

Figure 3. Effect of the foil width on the mean threshold voltage.

ed by the electrical Gurney energy method [6]. The flyer velocity could be computed by Equation (1).

$$V_f = \sqrt{2kJ_B^n}\left(\frac{M}{C} + {}^1\!/_3\right)^{-1/2} \tag{1}$$

where V_f is the flyer velocity, J_B is the burst current density, M is the mass of flyer in unit area, C is the mass of foil bridge in unit area, and k, n are coefficients.

For copper [7], n is 0.85, the relationship of J_B and S (section area of foil bridge) is $J_B \sim S^{-1/3}$, so one could get Equation (2):

$$V_f = \sqrt{2kS^{-0.14}}\left(\frac{d_f\,\rho_f}{d_e\rho_e} + {}^1\!/_3\right)^{-1/2} \tag{2}$$

where d_f, d_e are the thicknesses of flyer and metal foil, ρ_f, ρ_e are the densities of flyer and metal foil.

From Equation (2) one could get that the flyer velocity relies on the foil bridge width in case that the foil material, flyer material, and flyer thickness remain constant. Given that the initiation of exploding foil initiators only depends on flyer velocity from above analysis, the sensitivity of exploding foil initiators is only related to foil bridge width at this situation. The bigger the foil bridge is, the bigger is the section area and the current density and the resulting flyer velocity. In another way, at critical velocity to initiation of exploding foil initiators, the smaller section area and foil bridge width are, the bigger is the density of current and the smaller is the initiation voltage. Thus, reducing the foil bridge width will decrease the mean threshold voltage of exploding foil initiators. The theoretical analysis is in agreement with the test results in Figure 3.

3.2 Influence of the Foil Thickness on the Sensitivity of Exploding Foil Initiators

The exploding foil initiators with 3 μm (test No. 5) and 4 μm (test No. 4) foil thickness, which have similar foil bridge width, flyer thickness, and barrel length were tested according to the up-and-down method. The test results are illustrated in Figure 4, which shows that the mean threshold voltage of the exploding foil initiators with 4 μm foil thickness is 1995 V, meanwhile of 3 μm is 1750 V. The voltage is reduced by about 13 % as the foil thickness decreases from 4 μm to 3 μm.

However, the exploding foil initiators with smaller foil bridge width (0.2 mm) have different performance [4]. The sensitivity of exploding foil initiators changes only slightly when foil thickness is increased from 3 μm to 6 μm [4]. The variation of the mean threshold voltage is less than 4 %.

The amount of energy required for exploding the foil bridge is associated with foil thickness and foil bridge

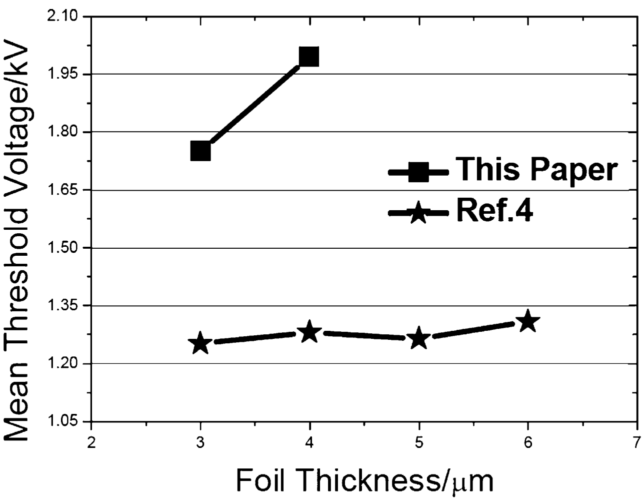

Figure 4. Effects of the foil thickness on the mean threshold voltage.

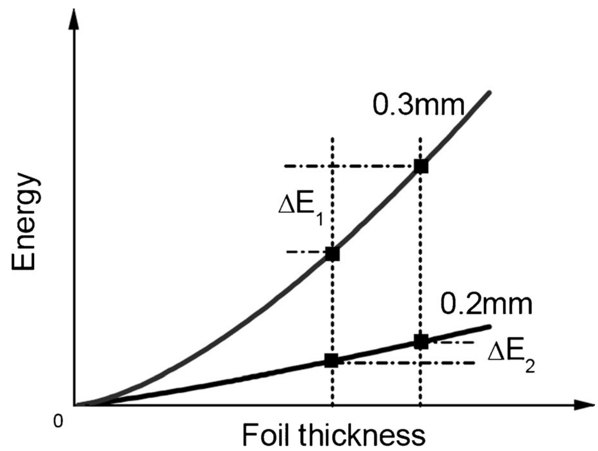

Figure 5. Dependence between energy for metal explosion and foil thickness.

width. The amount of energy rises with increasing foil thickness or foil bridge width. When the foil thickness increases from 3 μm to 4 μm, the increment energy (ΔE_1) for exploding a foil bridge with a width of 0.3 mm is greater than that (ΔE_2) for a foil bridge width of 0.2 mm. The theoretical explanation is illustrated in Figure 5.

Reducing the foil thickness thus decreases the mean threshold voltage of exploding foil initiators, yet the improvements of the sensitivity from decreasing foil thickness narrow as foil width becomes smaller.

3.3 Influence of the Flyer Thickness on the Sensitivity of Exploding Foil Initiators

Exploding foil initiators with 25 μm (test No. 3) and 50 μm (test No. 2) flyer thickness, which have similar foil bridge width, foil thickness, and barrel length were tested according to the up-and-down method. The test results are illustrated in Figure 6, which shows that the mean threshold voltage of exploding foil initiators with 50 μm flyer thickness is 1770 V, whereas that of foil initiators of 25 μm flyer thickness is 1440 V. The voltage reduces by about 20% as flyer thickness decreases from 50 μm to 25 μm.

As shown in Figure 5, the conclusion from Ref. [4] confirms the test results of this paper. Reducing the flyer thickness will decrease the mean threshold voltage of exploding foil initiators greatly, and those with 12.5 μm flyer thickness have best performance according to Ref. [4].

3.4 Influence of the Barrel Length on the Sensitivity of Exploding Foil Initiators

Exploding foil initiators with 0.2 mm (test No. 5) and 0.4 mm (test No. 6) barrel length, which have similar foil bridge width, foil thickness and flyer thickness were tested according to the up-and-down method. The test results are illustrated in Figure 7, which shows that the mean thresh-

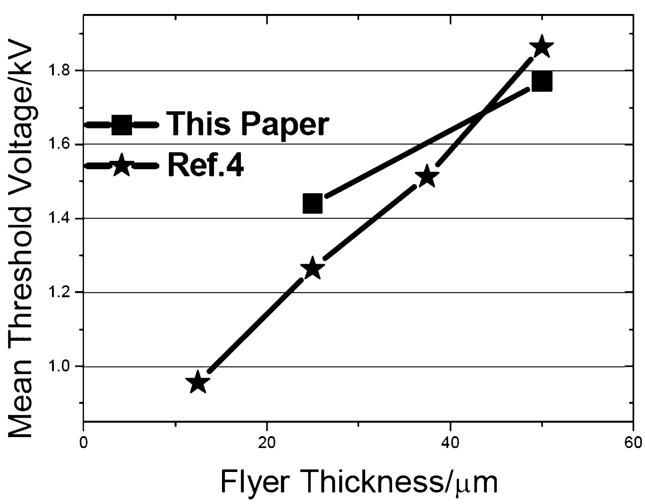

Figure 6. Effect of the flyer thickness on the mean threshold voltage.

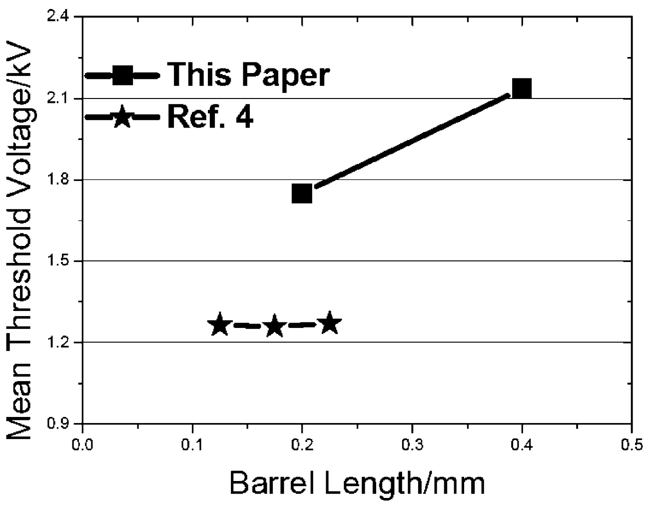

Figure 7. Effect of the barrel length on the mean threshold voltage.

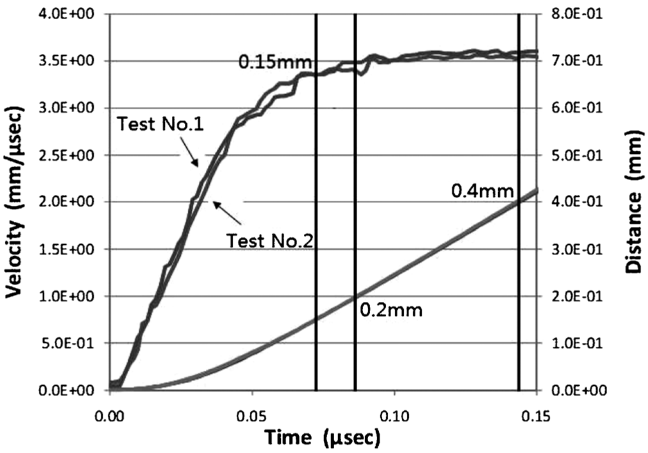

Figure 8. Velocimetry measurement of SLIP-coated all-dry chip slapper [8].

old voltage of the exploding foil initiators with 0.4 mm barrel length is 2135 V, whereas of that 0.2 mm barrel length is 1750 V. The voltage is reduced by about 18% as the barrel length decreases from 0.4 mm to 0.2 mm.

This phenomenon reveals that the flyer velocity is probably decreasing in the flight path from 0.2 mm to 0.4 mm and consequently a higher mean threshold voltage.

However, as illustrated in Figure 7, there is only minor influence on the sensitivity of exploding foil initiators in the barrel length range from 0.125 mm to 0.225 mm as reported in Ref. [4]. Herein it is suggested that the flyer has been fully accelerated to a maximum velocity before 0.125 mm. The velocimetry measurements of exploding foil initiators performed at LLNL [8] show that the flyer velocity reaches over 90% of the maximum at 0.15 mm and that there is only little increase in the velocity in the distance from 0.2 mm to 0.4 mm. Figure 8 revealed no evidence of velocity decreasing.

Theoretically, after vaporization of the metal bridge, the pressure behind the flyer decreases sharply. Correspondingly, the velocity of the flyer is increasing fast at first and slowly after a certain distance, which is similar to the observation depicted in Figure 8. The velocity profiles thus confirm the results reported in Ref. [4].

The reason that the mean threshold voltage reduces so distinct when the barrel length decreases from 0.4 mm to 0.2 mm is flyer pose, which will get worse as the barrel length extends. The flyer could incline in the manufactured barrel, which is not of ideal cylinder shape. The incline of flyer will bring on big angle and smaller interface of impact, which will enlarge the initiation energy because of diameter effect. Exceeding a barrel length of 0.15 mm has thus few effect on the sensitivity of exploding foil initiators, yet its manufacture quality is of great influence.

4 Conclusions

In order to study on the effects of foil bridge width, foil thickness, flyer thickness, and barrel length on the sensitivity of exploding foil initiators, a number of firings were carried out to investigate the sensitivity of exploding foil initiators by the up-and-down method. They were characterized by their mean threshold voltage. The results show:

(1) The mean threshold voltage of exploding foil initiators is reduced by 16% as the foil bridge width decreases from 0.4 mm to 0.3 mm, which means that reducing the foil bridge width could decrease the mean threshold voltage of exploding foil initiators. This was also proved by theoretical analysis.
(2) Reducing the foil thickness could decrease the mean threshold voltage of exploding foil initiators but a smaller foil bridge width will lower the extent of improvements.
(3) The mean threshold voltage of exploding foil initiators is reduced by 20% as the flyer thickness decreases from 50 μm to 25 μm, which is an efficient way to improve the sensitivity of exploding foil initiators.
(4) The flyer accelerates to over 90% maximum velocity after flying 0.15 mm in a fine barrel, which reveals that exceeding a barrel length of 0.15 mm has only little effect on the sensitivity of exploding foil initiators. Yet the manufacture quality has high influence.

Acknowledgments

The support of this work by co-workers in Pyrotechnics Laboratory, Institute of Chemical Materials, CAEP is gratefully acknowledged.

References

[1] W. Prinse, G. Scholtes, A Development Platform for a Microchip EFI, *52nd Annual Fuse Conference*, Sparks, NV, USA, May 13–15, **2008**
[2] Q.-B. Fu, X.-H. Jiang, F. Guo, L.-L. Wang, L. Wang, Effect of Exploding Foil Size on Flyer Velocity (in Chinese), *Acta Arm. II* **2010**, *31*, 434–436
[3] Z.-W. Han, E.-Y. Chu, K.-X. Wang, X. Ren, K.-H. Han, Y. Qian, H.-H. Tong, Study on the Relationship between the Thickness of Exploding Foil and Its Electrical Explosion Performance Sensitivity of Slapper Detonator (in Chinese), *Init. Pyrotech.* **2009**, *9*, 8–10
[4] J.-S. Hwang, M.-H. Lee, S.-M. Lee, H.-J. Ko, D.-I. Kang, K.-B. Bang, A Study on the Factors Affecting the Fire Sensitivity of Exploding Foil Initiators, *31st International Pyrotechnics Conference*, Fort Collins, CO, USA, June 11–16, **2004**
[5] F. E. Walker, R. J. Wasley, Critical Energy for the Shock Initiation of Heterogeneous Explosives, *Explosivstoffe* **1969**, *17*, 9
[6] S. C. Schmidt, W. L. Seitz, J. Wackerle, *An Empirical Model to Compute the Velocity Histories of Flyers Driven by Electrically Exploding Foils*, Report LA-6809, Los Alamos National Laboratory, Los Alamos, NM, USA, **1977**
[7] P. L. Stanton, *The Acceleration of Flyer Plates by Electrically Exploded Foils*, Report SAND-75–0221, Sandia Laboratories, Albuquerque, NM, USA, **1975**
[8] R. Chow, M. Schmidt, *Advanced Initiation Systems Manufacturing Level 2 Milestone Completion Summary*, Report LLNL-TR-417546, Lawrence Livermore National Laboratory, Livermore, CA, USA, **2009**.

Received: August 20, 2013
Revised: November 3, 2013
Published online: January 23, 2014

