Theoretical low-energy design of exploding foil initiator

Zehao Wang, *Qingxuan* Zeng, and *Mingyu* Li*

School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China

Abstract. In order to promote the development of miniaturization, low-energy and integration of exploding foil initiator, its low-energy design, preparation and tests were studied. It is expected to control the initiation voltage less than 1000 V. Based on the mechanism of bridge electrical explosion and driving flyer, the performance of exploding foil initiator at different parameters of bridge, flyer and barrel was calculated, which indicates an optimal matching relationship among component parameters as the bridge size of 0.2×0.2×0.006 mm, the flyer thickness of 12~22 μm and the barrel hole size of Φ 0.3×200~350 μm.

1 Introduction

Exploding foil initiator (EFI) is the preferred pyrotechnics for future weapon equipment because of the characteristics of high reliability, high instantaneity and high safety. It operates to initiate the explosive through the impact of flyer at a high velocity driven by the electrical explosion of metal foil. In order to improve its application range in weapon and ammunition systems, miniaturization, low-energy and integration have gradually become the development directions of exploding foil initiator system.

Numerous studies have been conducted to optimize the performance [1-4]. Since 1980s, Sandia National Laboratories have been engaged in the improvement of EFI [5], when new technologies including microelectromechanical systems (MEMS) and low temperature co-fired ceramics (LTCC) were applied to the preparation, whose system volume has been greatly compressed to about 0.97~1.76 cm^3 [1]. The slapper detonators of Blue Chip developed by Excelitas Technologies company [6] is a highly representative series of commercial EFI, whose latest product could be induced at a capacitance of 0.1 μF and an initiation voltage of 1030 V. In addition, e2v [7] and TNO [8] companies both considerably contributed to the low-energy and integration design of EFI, and various products have been developed for different application.

For given capacitor, the capacitor voltage is the key of low-energy design of EFI. In this article, the performance mechanism of bridge electrical explosion and driving flyer was studied to explore the optimal relationship among component parameters of bridge, flyer and barrel for an initiation voltage less than 1000 V.

---

[*] Corresponding author: mingyuli@163.com

2 Theoretical model

The performance of EFI consists of 2 processes: bridge electrical explosion and driving flyer. BZB is a 2-D calculation program developed based on the mechanism of bridge electrical explosion, which would accurately calculate electrical explosion curves in bridge after importing the resistivity model of corresponding bridge material [9].

Cu is the most widely applied bridge material [6]. Induced by the high-density pulse current, the Cu bridge rapidly heats up and undergoes a series of phase transitions, ultimately transforming into high-temperature and high-pressure plasma induced by high-density pulse current. Based on phase transitions, the electrical explosion process is divided into 5 stages: solid heating, melting, liquid heating, vaporization, intrinsic explosion and plasma. The resistivity of Cu bridge in each stage is always regarded as a function of temperature, expressed as follows [10, 11]

$$\rho(\mu\Omega\cdot\mathrm{cm})=\begin{cases}\rho_{\mathrm{n}}+k_{\mathrm{s}}(T-300) & 300\le T<T_{\mathrm{m}}\\ A_{\mathrm{m}}+B_{\mathrm{m}}H+C_{\mathrm{m}}H^{2} & T=T_{\mathrm{m}}\left(H_{1}\le H<H_{2}\right)\\ A_{\mathrm{l}}+B_{\mathrm{l}}H+C_{\mathrm{l}}H^{2} & T_{\mathrm{m}}<T<T_{\mathrm{V}}\left(H_{2}\le H<H_{3}\right)\\ \rho_{\mathrm{V}}+k_{\mathrm{V}}\dfrac{H_{\mathrm{de}}}{H_{\mathrm{V}}} & T=T_{\mathrm{V}}\left(0\le H_{\mathrm{de}}<H_{\mathrm{V}}\right)\\ k_{\mathrm{x}}\dfrac{n_{\alpha}}{n_{\mathrm{e}}}\gamma_{\mathrm{V}}Z^{2}T & T_{\mathrm{V}}<T<T_{\mathrm{cr}}\\ \dfrac{m_{\mathrm{e}}}{e^{2}n_{\mathrm{e}}\tau_{\mathrm{e}}A^{\alpha}} & T\ge T_{\mathrm{cr}}\end{cases}\tag{1}$$

where, ρ_{n}, ρ_{V} are the resistivity at room temperature and onset point of vaporization, respectively; H_{V} is the latent heat of vaporization; H_{de} is the specific deposited electrical energy during the vaporization stage; k_{x} is the correction coefficient for the electrical resistivity of metal gas; n_{α}, n_{e} are the atomic and electron density, respectively; γ_{V} is the expansivity of volume; Z is the effective charge quantity; m_{e} is the electronic mass; e is the elementary charge; τ_{e} is the electron relaxation time; A^{α} is a parameter relevant to Fermi-Dirac integral; T_{m}, T_{V} and T_{cr} are the melting point, boiling point and critical temperature, respectively; H is the specific enthalpy; H_1, H_2 and H_3 are the specific enthalpies of the melting onset point, melting end point (i.e. liquid heating onset point) and liquid heating end point, respectively. For Cu bridge, the values of some parameters are shown in Table 1.

Table 1. Parameter values of the resistivity model of Cu bridge.

T_{m}/K	T_{V}/K	T_{cr}/K	ρ_{n}/μΩ·cm	ρ_{V}/μΩ·cm	H_{V}/(kJ·g^{-1})	H_1/(kJ·g^{-1})	H_1/(kJ·g^{-1})	H_2/(kJ·g^{-1})
1356	3000	8000	1.5875	38.4	4.731	0.425	0.671	1.536
k_{s}	k_{V}	A_{m}	B_{m}	C_{m}	A_{l}	B_{l}	C_{l}	
6.75×10^{-3}	19.5	-6.041	28.185	19.032	15.451	4.415	6.855	

FID is a 1-D lagrangian unsteady compressible hydrodynamics calculation program developed based on the actual process of plasma driving flyer, where the substrate, flyer and ionized bridge were treated as fixed wall, movable rigid body and real gas, respectively [12-14]. The equations are as follows

$$
\begin{aligned}
&\text{Mass Conservation Eq.} && v = v_0 \frac{\partial s}{\partial s_0} \\
&\text{Momentum Conservation Eq.} && \frac{\mathrm{d}u}{\mathrm{d}t} = -v\frac{\partial\left(p+q\right)}{\partial s} \\
&\text{Energy Conservation Eq.} && \frac{\mathrm{d}e}{\mathrm{d}t} = -\left(p+q\right)\frac{\mathrm{d}v}{\mathrm{d}t} + \frac{\mathrm{d}E}{\mathrm{d}t} \\
&\text{Motion Eq.} && \frac{\mathrm{d}s}{\mathrm{d}t} = u \\
&\text{Electrical Energy Eq.} && \frac{\mathrm{d}Q}{\mathrm{d}t} = PP\left(t\right) \\
&\text{EOS} && p = c_0^2\left(\frac{1}{v}-\frac{1}{v_0}\right)+\left(\gamma-1\right)\frac{e}{v}
\end{aligned}
\tag{2}
$$

where, v is specific volume; s is the displacement; u is the particle velocity; p is the pressure; q is artificial viscosity coefficient; E is the specific electrical energy; PP(t) is the specific electrical power; e is the specific internal energy; γ is the specific heat ratio, i.e. $\gamma=C_P/C_V$; v_0, s_0 and c_0 are the initial specific volume, initial displacement and initial acoustic velocity, respectively.

HNS-IV is the permissible explosive for EFI because of the characteristics of high safety, high thermal stability, and excellent sensitivity of short pulse shock. The $p^x\tau$ criterion [15] and James criterion [16] are 2 commonly applied shock initiation criteria for HNS-IV and they were revised by Guo et al. [17] as

$$
\begin{cases}
p^{2.08}\tau > 1.38\ \text{GPa}^{2.08}\cdot\mu\text{s} \\
\dfrac{0.1900}{\Sigma}+\dfrac{0.0954}{E}<1
\end{cases}
\tag{3}
$$

where, Σ is the specific kinetic energy, i.e. $\Sigma=u^2/2$, u is the particle velocity; E is the energy flux, i.e. $E=pu\tau$, τ is the pulse duration and for non-metallic flyer that is given by

$$
\tau = \frac{2d_{\mathrm{f}}}{D_{\mathrm{f}}}
\tag{4}
$$

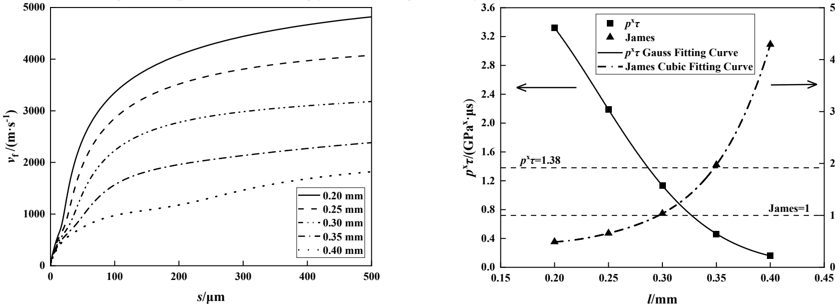
where, d_{f} is the flyer thickness; D_{f} is the shock wave velocity in flyer that is calculated by plane impact theory [18].

Thus, the performance of EFI at definite parameters can be calculated through Eqs. (1)~(4).

3 Results and discussion

The performance of EFI mainly depends on component parameters of bridge, flyer and barrel. The bridge size affects the output work of electrical explosion. The thickness of flyer determines the effect of short pulses during impact. The barrel thickness represents the acceleration distance Therefore, the performance was calculated at different bridge side lengths l, bridge thicknesses d_{b} or flyer thicknesses d_{f} when the capacitance C=0.24 μF and the capacitor voltage U_0=1000 V to explore the optimal relationship.

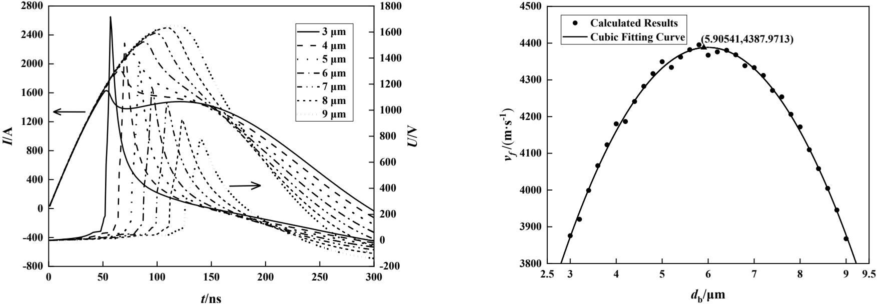
Fig. 1 shows the calculated results at different l. The flyer would be accelerated to a higher velocity by a bridge with smaller 2-D size. Meanwhile the HNS-IV could be initiated theoretically only at l=0.20~0.25 mm, because there is higher current density during capacitor discharging at a smaller *l*, which further results in more intense electrical explosion and higher specific energy loading on flyer.



(a) v_f-s (b) Impact initiation criteria (s=275 μm)

Fig. 1. Calculated curves of flyer driven by electrically exploded bridge at different side lengths.

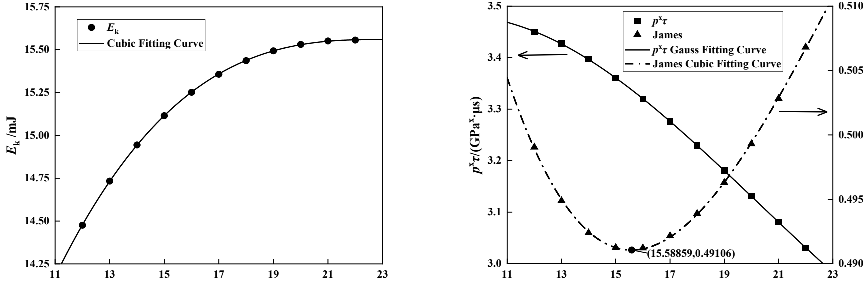
Fig. 2 shows the calculated results at different d_b. It illustrates that as d_b increases, the burst point is delayed with a reduced peak voltage, because the bridge resistance decreases and more deposited electrical energy is required to induce complete electrical explosion. However, the burst occurs too early at smaller d_b, resulting in lower deposited electrical energy. Fig. 2(b) illustrates the relationship between the impact velocity of flyer and bridge thickness is fitted as a cubic function of v_f=2295.619+706.251d_b-60.843d_b^2+0.211d_b^3 (R^2=0.99596) at a barrel thickness s=275 μm, indicating an optimal d_b of 6 μm.



(a) *I*/*U*-*t* (b) v_f-d_b (s=275 μm)

Fig. 2. Calculated results of electrical explosion and driving flyer of bridge at different thicknesses.

Fig. 3 shows the calculated results at different d_f. when the d_f increases within the range of 12~22 μm, the improvement of kinetic energy gradually becomes less significant, the $p^x\tau$ criterion expression decreases and James criterion expression reaches its minimum at d_f≈15.6 μm. While HNS-IV can always be theoretically initiated.



(a) E_k-d_f (s=275 μm) (b) Impact initiation criteria (s=275 μm)

Fig. 3. Effect of bridge electrical explosion driving flyer at different flyer thicknesses.

As for the barrel, the hole diameter equals the flyer diameter, which approximates 0.3 mm for *l*=0.2 mm. Fig. 1(a) illustrates that the improvement of the final flyer velocity gradually weakens with the increased *s*. To avoid the risk of the change of flyer motion state, it is suitable to control the *s* within the range of 200~350 μm.

In short, at a circuit of *C*=0.24 μF and U_0=1000 V, the optimal matching relationship is obtained as the bridge size of 0.2×0.2×0.006 mm, the flyer thickness of 12~22 μm and the barrel hole size of Φ 0.3×200~350 μm.

4 Conclusion

In summary, the mechanism of bridge electrical explosion and driving flyer was studied to design component parameters. At *C*=0.24 μF and U_0=1000 V, the optimal matching relationship among component parameters was obtained as the bridge size of 0.2×0.2×0.006 mm, the flyer thickness of 12~22 μm and the barrel hole size of Φ 0.3×200~350 μm. This work greatly contributes to the low-energy design of EFI.

The authors would like to acknowledge National Natural Science Foundation of China (Grant No. 11872013) for supporting this project.

References

1. S.K. Curtis, A.R. Church, 63rd Annual Fuze Conference (Kansas City, MO, 2020)
2. K. Wang, P. Zhu, C. Xu, Q. Zhang, Z. Yang, R. Shen, Micromachines 11, 550 (2020)
3. N.C. Nance, M.A. Amendola, C.J. Nance, US 010935352 (2020)
4. Z. Yang, P. Zhu, Q. Chu, Q. Zhang, K. Wang, H. Jian, R. Shen, Defence Technology 18, 1435-1444 (2022)
5. R.S. McEntire, P. Butler, 53rd Annual Fuze Conference (Lake Buena Vista, FL, 2009)
6. T. Wang, Beijing Institute of Technology (Beijing, 2022)
7. D. Seddon, B. Weller, S. Bower, 59th Annual Fuze Conference (Charleston, SC, 2016)
8. G. Scholtes, W. Prinse, 2007 Insensitive Munitions & Energetic Materials Technology Symposium (Miami, FL, 2007)
9. X. Hu, Beijing Institute of Technology (Beijing, 1998)
10. G.R. Gathers, International Journal of Thermophysics 4, 209-226 (1983)
11. Y. Zhao, Q. Zeng, Q. Liang, Acta Armamentarii 29, 902-906 (2008)
12. L. Liang, Z. Fan, X. Hu, Acta Armamentarii 20, 102-107 (1999)
13. Q. Zeng, Y. Zhao, Q. Liang, S. Yuan, Chinese Journal of Explosives & Propellants 31, 50-53 (2008)
14. Y. Zhao, Q. Zeng, C. Feng, Journal of Beijing Institute of Technology 19, 8-13 (2010)
15. H.R. James, Propellants Explosives Pyrotechnics 21, 8-13 (1996)
16. F.E. Walker, R.J. Wasley, Explosive Stoffe 1, 9-14 (1969)
17. J. Guo, Q. Zeng, M. Li, Q. Yu, Chinese Journal of High Pressure Physics 32, 6 (2018)
18. B. Zhang, Q. Zhang, F. Huang, Explosion Physics (2006)