Study on penetration-induced initiation of energetic fragment

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Abstract. In order to investigate penetration-induced initiation of energetic fragment penetrating target, PTFE/Al (mass ratio 73.5/26.5) pressed and sintered into a Ф8mm × 8mm cylinder. To form energetic fragment, the cylinder was put into a closed container made by 35CrMnSiA. The container is 12mm long, 2mm thick. Energetic fragments were launched by a 14.5mm ballistic gun with a series of velocities and the penetrate process was simulated by AUTODYN-3D. The results show that the stress peak of energetic material exceed the initiation threshold, and energetic material will deflagrate, when energetic fragments impact velocity more than 800 m/s. The research results can provide reference for designs of energetic warhead.

1. Introduction
Energetic fragments, also known as reactive material enhanced penetrator, which usually consists of energetic materials as core and is wrapped with high strength metal[1]. Because of strong penetrating ability and "class detonation" damage effect caused by large released chemical energy, the energetic fragment attracts both domestic and foreign scholar attention. Energetic fragment filled with different energetic material impact steel target was studied by Jun-feng Shuai[1] et al. The experiment results show that the deflagration effect of PTFE/Ti is better than PTFE/Al, damage capability of fragment increases with the shell thickness, and the target aperture by energetic fragment is 40% higher than that by inert fragment. JIANG Jian-wei[2] et al. Studied the strength model and state equation of PTFE/Al and verified the validity of the model by AUTODYN. Yin Yi-feng[3] analyzed dynamic behavior of reactive material enhanced penetrator impact target, and studied the structure parameters, projectile/target materials and impact conditions in detail.

In this paper, using AUTODYN to simulate energetic fragment penetrate target, and verified the validity of simulation by range test. Analyzed fragment velocity variation and internal pressure of energetic material when energetic penetrate target in different velocities and angles. To provide guidance for engineering application of energetic materials in terminal ballistics.

2. Range Test
Before experiment, preparing energetic material. Mixing Al powder and PTFE by mass ratio 26.5/73.5, and pressed into Ф8mm × 8mm cylinder by press machine, then sintered in vacuum furnace. Sintering temperature in 365 ºC~385 ºC, the heating rate was about 10 ºC/min, density of sintered material is about 2.4 g/cm³. Finally, the energetic material was filled into 35CrMnSiA shell and confined with an end cap. Figure 1 shows the test site layout, target is 10 m away from ballistic gun, placed high-speed camera (model:
PHANTOM220) 10 m away from target’s left side, shooting frequency is 3000fps. using 14.5mm ballistic
gun launching the energetic fragment with sabot, see Figure 2, adjust velocities by changing charge, target
material is 4340 steel in 6mm thick. Test consumes 10 rounds of projectiles, and launch velocities is 600
m/s~1500 m/s, interval is about 100 m/s. Part of results are shown in Table 1.

The results show that the energetic fragments will deflagrate, when velocity is higher than 800 m/s, contrarily, there is no deflagration, when velocity below 800 m/s.

![Figure 1. Test site layout](image)

![Figure 2. Energetic fragment and propellant cartridges](image)

| Table 1 | typical fragment penetrating the target |
|---------|----------------------------------------|
| Velocity(m/s) | $t=0.20$ ms | $t=0.23$ ms | $t=0.26$ ms |
| 706       |  |
| 812       |  |
| 902       |  |

3 Numerical Simulation

3.1 Computational model
According the size and metal of energetic fragments used in experiment to build up fragment model, and
target model is a 6 mm thick circular plate made by 4340 steel. Considering the symmetry of structure, a 1/2
model will be established with symmetry constraint by AUTODYN-3D, using mm-mg-μs unit system,
Lagrange algorithm and hexahedron mesh. In order to clearly describe penetration, a schematic sketch for
Fragment impact target in different angles is depicted, \( V \) is penetration velocity, \( \alpha \) is target angle. Finite element model and geometric model are shown in figure 3.

![Figure 3](image)

**Figure 3** The finite element model of energetic fragment penetrating target and geometrical model

### 3.2 Material model

The shock EOS for most metals and the Johnson–Cook plasticity model are adopted to describe the dynamic response of fragment shell, energetic material and target. To prevent the mesh distortion during calculation, all materials added erosion algorithm. The strain values of PTFE/Al, 35CrMnSiA and 4340 steels are 0.8, 1.5 and 1.5, respectively. The material parameters used in simulation are given in Table 2.

| Parameters | PTFE/Al | 35CrMnSiA | 4340 steel | Parameters | PTFE/Al | 35CrMnSiA | 4340 steel |
|------------|---------|------------|------------|------------|---------|------------|------------|
| \( A \) (MPa) | 8.044 | 1500 | 792000 | \( G \) (MPa) | 666 | —— | —— |
| \( B \) (MPa) | 250.6 | 3000 | 510000 | \( \gamma \) | 0.9 | —— | —— |
| \( N \) | 1.8 | 0.2 | 0.26 | \( c_0 \) (m/s\(^3\)) | 1450 | —— | —— |
| \( C \) | 0.4 | 0.014 | 0.014 | \( S \) (m/s\(^3\)) | 2.258 | —— | —— |
| \( \theta_m \) (k) | 463 | 1793 | 1793 | \( \dot{\varepsilon} \) (s\(^{-3}\)) | —— | 206 | —— |
| \( \theta_r \) (k) | 299 | 300 | 299 | \( E \) (GPa) | —— | 206 | 200 |
| \( \rho \) (kg/m\(^3\)) | 2.40 | 7.83 | 7.8 | \( m \) | —— | 1.03 | 0.94 |

### 3.3 Effect of velocity on internal stress distribution of energetic materials

In simulation, the energetic fragments velocities is 600 m/s~1500 m/s and interval is 100 m/s. Due to small strain rate of energetic materials, the reference [4] shows that energetic material internal stress peak in posterior good agreement with theoretical calculations through theoretical calculation and numerical simulation. Therefore, setting observation points in posterior of energetic material before calculation. Plot the calculate results into line, and then compared with experimental results in reference [5] and the initiation threshold \( \sigma_c \) in reference [6]. The relationship between impact velocity and internal stress is shown in figure 4.

From figure 4(a), we can notice that the internal stress peak of energetic material is lower than initiation threshold and the material didn’t deflagrate when penetrate velocity is lower than 800 m/s, which is conformed to experimental result. And the figure 4(b) shows that the stress peak of energetic material increases with impact velocities. Because of steel shell used in this paper, the energetic material is subjected to large stress. Therefore the stress is higher than that in reference [6], while the trend of calculated results are consistent with the experimental results[6], combining above experimental results can prove the validity of the computational model.
3.4 Explosive Behavior of Targets with Different Angle of Energetic Fragment

When PTFE/Al subjected to shock wave, it may ignite and deflagrate, so its chemical reaction rate is related to impact condition closely. If the overpressure of energetic material reaches or exceeds the threshold pressure \( \sigma_c = 3.6 \text{GPa} \) for deflagration\[6\], the energetic material will deflagrate. Penetration-induced initiation behavior of energetic fragments, means its penetration ability and deflagration performance, now analysis velocity decay and internal stress of fragments penetration 6 mm thick 4340 steel target in 800 m/s, and determine whether deflagration occurs. In order to clearly observe the internal stress peak of energetic materials, nine observation points are uniformly set on energetic materials, as shown in figure 5.

Figure 5. The internal observation points of energetic materials

Figure 6 shows the velocity decay curve of energetic fragments penetrating the target at different angles and the distribution of internal stress peak of the energetic materials. From figure 6(a), we can see all fragments penetrated through the target effectively. When impact angles is 0°, 5°and 10°, the velocity fluctuates is obviously, velocity decreases rapidly at 0~15μs, and becomes slowly after 15μs, all fragments’ residual velocities are more than 300 m/s. In 0~18μs, the velocity curves of 15°, 20°and 25° fluctuates is not obvious, compared with the velocity curves of 0°, 5°and 10°. It is attributed the great stress generated instantaneously during the fragments impacting the target with relatively large impact angle. With the penetration, compressive stress gradually unloading, acceleration similar to the linear changes so that velocity curve is similar to a straight line. The change of velocity curve decreases and trends to be gentle after 20μs. Residual velocity is between 200 m/s to 260 m/s, lower than the velocity for 5°, 10°and 15°, which indicates that the bigger impact angle, the greater consume energy of fragment penetrating target, so that the fragment leave less kinetic energy and lower velocity. From figure 6(b), the trends of stress is consistent except individual jumping points of energetic materials at 5°. The stress peak of energetic material exceeds the initiation threshold and occur deflagration when impact angle is 0°, 5°and 10°, while the internal stress peak is below initiation threshold and can’t deflagration at 15°, 20°and 25°.
4. Conclusions

In this paper, through the experiment and the simulation of energetic fragment impact, we received following conclusions:

1) The energetic material will deflagrate when the penetrate velocity exceeding 800m/s.
2) The residual velocity of the fragment decreases with the increase of angle. When the angle is 0°~10°, the internal stress peak of energetic material exceeds the initiation threshold, and when the angle is 15~20°, the internal stress peak is below the initiation threshold.
3) The results of numerical simulations of the energetic fragments penetrating target have good agreement with the experimental results.
4) The results of this study can provide reference for the design of energetic fragment warheads and damage research.

References

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