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Ballistic Characteristics on Oblique Penetrating Multi-Layer Aluminium Targets by Annular Groove Projectile

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Abstract. With the development of complex terminal effects, the semi penetration effect of annular groove projectiles on multi-layer targets has obtained increasing attention. In this paper, based on the theory of cavity expansion, a comparative analysis model is established for the oblique penetration of annular groove projectile and ogive-nosed projectile into multi-layer targets. The FEM analysis software LS-DYNA is used to simulate and calculate the time history curves of projectile velocity, axis deviation angle, and axis angular velocity. In addition, the micro rheological behavior of the target material in the groove during oblique penetration was studied. The results show that the radial offset of the annular groove projectile is less than that of the pointed projectile, and the larger the landing angle, the greater the projectile offset. The penetration resistance of target decreases with the increase in layers of target, while the DOP and lateral deviation of the projectile increase. This analysis model can provide analytical basis for related applications.

Keywords. Ordnance science and technology, annular groove projectile, multi-layered targets, numerical simulation.

1. Introduction

Armor piercing and penetration are the traditional research fields of weapons and ammunition, and kinetic energy penetration into multi-layer protective armor has been widely and deeply studied. With the advancement and development of protective technology and the new requirements for endpoint effects, a shaped projectile, the annular groove projectile (AGPs) [1], has emerged. Scientific researchers have extensively studied the effects of regular warhead attack and landing angles on penetration trajectory: Goldsmith elaborated on the theoretical research, numerical simulation, and experimental techniques of non-ideal projectile target effects such as oblique impact, moving target plate, and jump flight [2]; Chen summarized the engineering research issues of armor piercing and penetration since 2009. At the same time, a detailed analysis was conducted on the oblique penetration and armor penetration of slender pointed rigid projectiles into metal targets [3]. There is relatively little research on the penetration trajectory of irregular warheads with different penetration capabilities.

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In this paper, we use ANSYS/LS-DYNA finite element software to establish penetration bodies with pointed and annular groove structures of the same size. Under different initial landing conditions, low-speed penetration and armor piercing simulations of 2024 aluminium alloy 4-layer medium thick target plates are conducted to study the ballistic characteristics and attitude variation of projectile oblique penetration, providing a theoretical basis and foundation for whether the projectile can hit the target according to the predetermined landing attitude in the future.

2. Establishment and Validation of the Model

This section analyses the impact of oblique penetration of projectiles into the interface of multi-layer target plates, and establishes a numerical simulation model for dynamic oblique penetration of multi-layer targets under the action of annular groove projectiles (AGPs) and ogive projectiles (OPs).

2.1. Theoretical Model

The deformation and failure mode of the target plate under the oblique penetration of a pointed oval shaped projectile are mainly manifested as ductile hole expansion. During the penetration process of the projectile into the target plate, the projectile is subjected to an asymmetric force acting on it, resulting in a certain degree of deflection of the projectile; As the direction angle of the projectile changes during the initial penetration stage, there is a contact separation contact between the lower edge of the projectile and the curved hole of the target plate, while there is a contact separation between the upper edge of the projectile and the target plate. This phenomenon is the weak separation effect of the projectile's oblique penetration; During the penetration process, stress propagation reaches the interface between multiple layers of targets, causing reflection. The vertical tensile force between target plates cannot be transmitted, resulting in significant separation. This is significantly different from single-layer homogeneous targets, resulting in unpredictable deviations in the oblique penetration trajectory of the projectile. This phenomenon is known as the interface effect of multi-layer target. As shown in Figure 1.

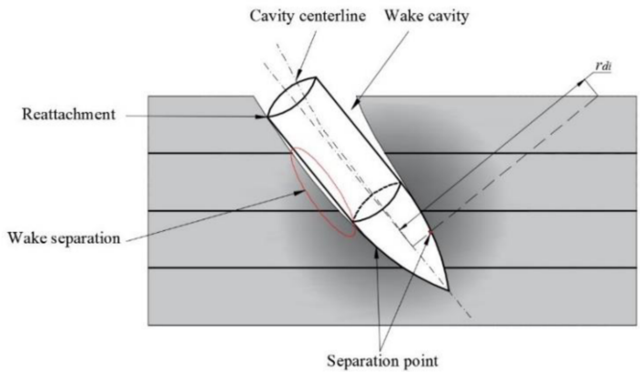


Figure 1. Model of oblique penetration into multilayer targets.

2.2. Geometric Modeling of Projectile and Target

Based on the experience of warhead design engineering, armor piercing or semi armor piercing projectiles usually adopt an oval design, with a caliber radius head (CRH), which is generally between 3 and 5 [4]. In this article, the projectile, with CRH equals 5, is selected as a single circular groove structure based on ogive nose, as shown in Figure 2.

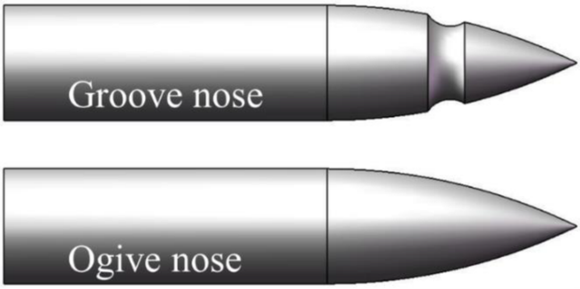


Figure 2. Model of oblique penetration into multilayer targets.

2.3. Finite Element Model

With the finite element method (FEM) analysis software ANSYS/LS-DYNA, we established a numerical simulation model for the oblique penetration of rigid pointed oval shaped projectiles into multi-layer target plates. The targets are all equipped with eight node hexahedral elements, and the element algorithm is the Lagrangian algorithm. The model adopts 1/2 3D modeling and sets symmetry plane constraints through Cnstrnd-GLOBAL; Refine the grid in the area of 2 times the projectile diameter at the centre of the target plate, with a central grid size of 0.25 × 0.25 × 0.5mm. The FEM of the projectile and target is shown in Figure 3, with 28290 projectile grids and 640000 target plate grids.

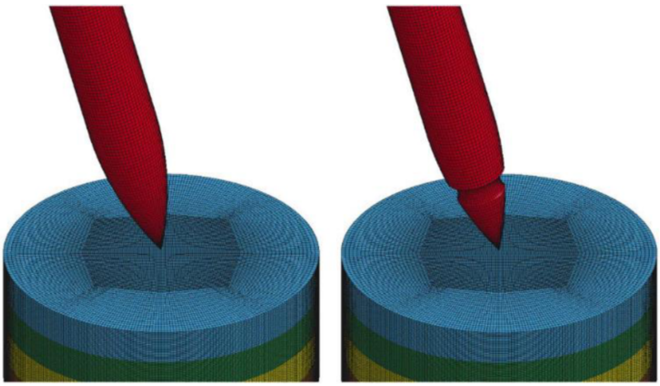


Figure 3. The FEM of the projectile and targe.

In the contact setting, (*ERODING_SURFACE_TO_SURFACE) is used between the projectile and the concrete, and (*HOURGLASS) is used in the target plate model to better reflect nonlinear problems such as large deformation and failure of the target plate material[5].

2.3.1. Material parameters of Projectile and Target

Due to the significantly higher strength performance of 7055 aluminum alloy compared to 2024-O aluminum alloy target plate, and the small deformation of the projectile during low-speed penetration, in order to avoid ballistic deviation caused by bending deformation and mass loss of the projectile during penetration, the projectile adopts a rigid material model (*MAT_RIGID) with a density of 2.84g/cm3 and an elastic modulus of 71.08GPa.

The target material model uses the Johnson Cook [6] equation to describe the constitutive state of the material under deformation failure conditions. Its constitutive equation can be expressed as

$$\sigma_{eq} = \left(A + B\varepsilon_{eq}^{n}\right)\left(1 + \dot{\varepsilon}_{eq}^{*}\right)^{C}\left(1 - T^{*m}\right) \tag{1}$$

where σ_{eq} is the equivalent stress, ε_{eq} is the equivalent plastic strain, *A, B, n, C,* and m are materials constants and $\dot{\varepsilon}_{eq}^{*} = \dot{\varepsilon}_{eq}/\dot{\varepsilon}_{0}$ is the dimensionless strain rate where $\dot{\varepsilon}_{eq}$ and $\dot{\varepsilon}_{0}$ are the strain rate and a user-defined strain rate, respectively. The modified Johnson-Cook material model has successfully been used to model impact on aluminum target. Material model parameters used in simulations are shown in Table 1.

Table 1. Material properties and modified Johnson-Cook model parameters[7].

Parameter	**A/(MPa)**	**B/(MPa)**	**C**	**n**	**m**	$T_r/(K)$	$T_m/(K)$
Target	370	179.8	0.012	0.73	1.53	293	933
Parameter	$\rho_t/(\mathrm{kg}/m^3)$	$E/(\mathrm{GPa})$	D_1	D_2	D_3	D_4	D_5
Target	2770	73.1	0.136	0.136	-1.56	0.011	1.014
Parameter	ro	e	pr	sigy	etan	fs	vp
Projectile	2.84	71.08	0.324	0.019	0.008	0.8	0

3. Results and Discussions

Numerical simulations of AGPs and OPs were conducted using LS-DYNA. Four speeds were selected for simulation to compare and study penetration performance.

3.1. Process of Oblique Penetration into Multi-Layer Targets

The numerical simulation results of two types of projectiles penetrating the 4×20mm 2024-O aluminum target at the speed of 300m/s were obtained. Taking the AGP obliquely penetrating the aluminum alloy target at a 15 ° landing angle as an example, the von mises stress cloud map of the penetration process at different times is shown in Figure 4. The typical physical phenomena of metal targets have been well simulated. The overall bending deformation of the target plate is very small, and the local deformation is relatively large. The main failure form is petal cracking.

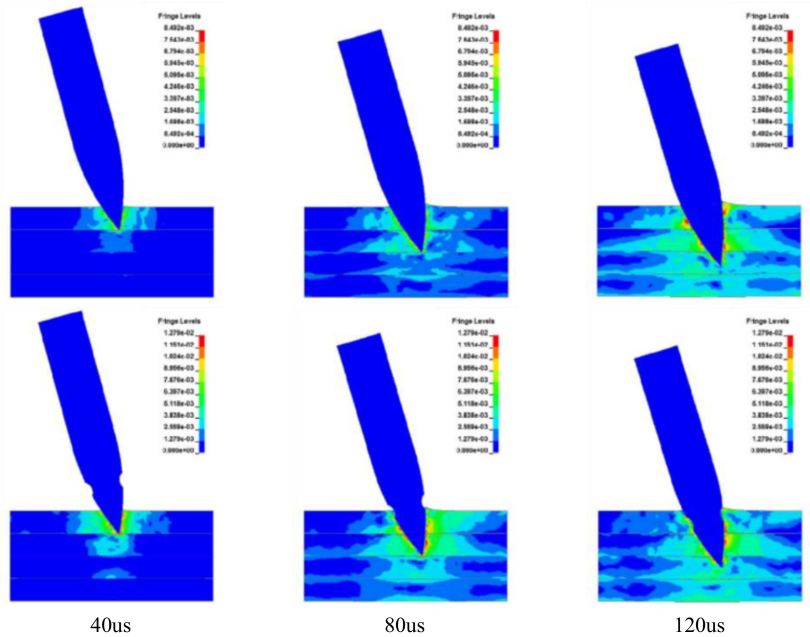


Figure 4. Von mises stress cloud map of AGPs and OPs oblique penetration into aluminum targets.

3.2. The Trajectory of Penetration

Due to the influence of the target interface, the penetration trajectory of AGP is somewhat different from that of OP. In the early stage of penetration, the force area on the head of the projectile is small, and the overall motion of the projectile remains approximately linear. As the projectile continues to penetrate, the radial force on the side of the projectile gradually increases, and the asymmetric force caused by oblique penetration intensifies the inclination of the projectile axis. After the pit is opened, the projectile speed decreases at this time. The lower side of the projectile is subjected to a counterclockwise torque, causing the axis of the projectile to deflect, approaching the deflection angle when the projectile is cratered.

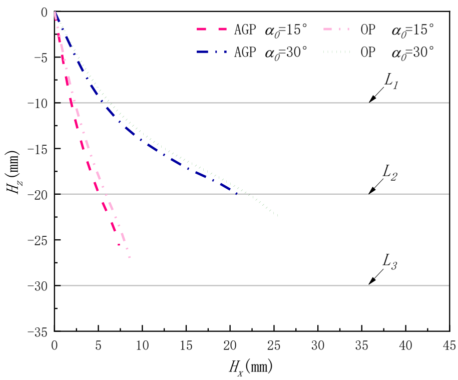


Figure 5. Comparison of AGP penetration trajectories.

Figure 5 shows the motion trajectory curves of two types of projectiles penetrating armor under different initial conditions. L1-L3 in the figure corresponds to the 1st to 3rd layer interfaces in the multi-layer target, respectively. From the comparison in Figure 5, due to the influence of grooves, it can be seen that the DOP of AGP is significantly lower than that of OP,the trajectory of OP is smoother, while the axis offset of AGP is smaller. This is because when the groove on the lower axis side of AGP invades the upper surface of the target plate, some of the target plates undergo elastic-plastic deformation and squeeze into the groove, reducing the projectile deflection force. For the same type of projectile, the larger the landing angle within the range of 5 ° to 30 °, the greater the radial offset of the projectile.

3.3. Analysis of Ballistic Characteristics of AGP and OP

The variation of the projectiles deceleration, velocity and depth of penetration (DOP) are exhibited and analyzed. Figure 6 compares the results of numerical simulation, proving that AGP has a deeper DOP than OP. As aforementioned, the nose shape has a significant influence on the DOP during low-speed impact.

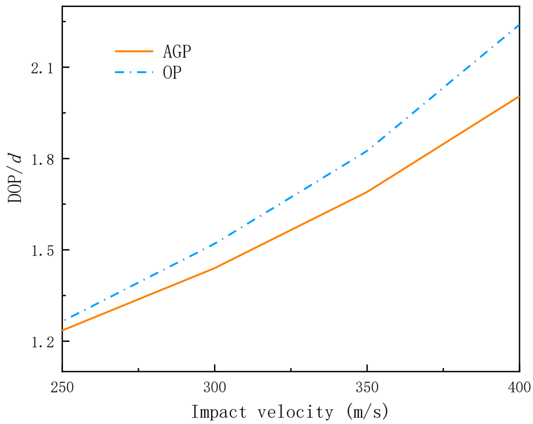
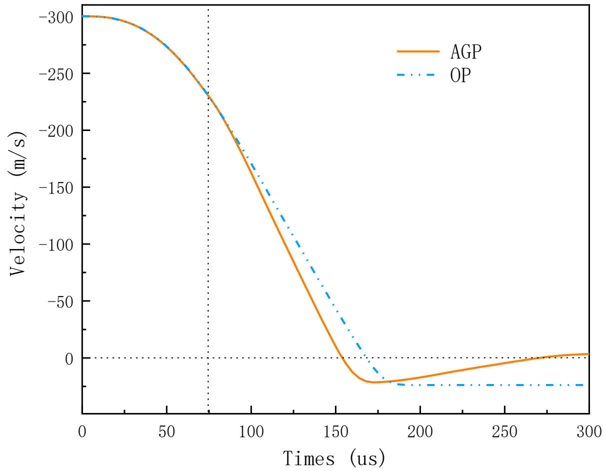


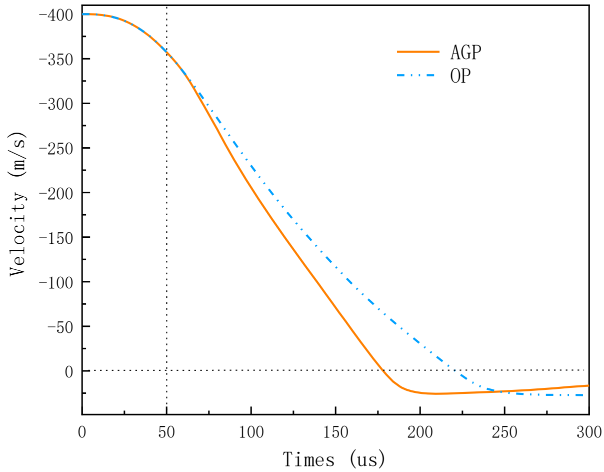
Figure 6. Dimensionless penetration depth history.

Figure 7 exhibits the velocity time-history curves with different impact velocities (300m/s and 400m/s). It exhibits the axial penetration resistant up to maximum rapidly, then it keeps the value at a high level. When velocity decays to zero, the resistance starts to reduce.

Observe the velocity curve characteristics of the OP, such as 76us in an impact of 300m/s. In addition, the velocity first decreases with the penetration process, and then there is an increasing segment when the value reaches zero. Due to the projectile failing to penetrate the target and the elastic recovery of the target, the displacement of the projectile slowly decreases after reaching the maximum DOP. This phenomenon is typical of the rebound stage. The AGP exhibits a similar trend in the velocity drop stage, and the velocity drop is greater. It was observed that the AGP velocity gradually tends to zero after reaching the maximum reverse direction, indicating that the projectile groove plays a certain role in embedding and preventing the projectile from being ejected from the target.



(a) 300m/s



(b) 400m/s

Figure 7. The velocity time-history curves with different impact velocities.

4. Conclusions

This article conducts theoretical analysis and numerical simulation on the oblique penetration of AGP and OP projectiles into multi-layer aluminum targets. It compares the projectile velocity, overload, angular velocity, and axis deviation angle during the oblique penetration process of projectiles into target plates at the same initial velocity and different landing angles, and studies the influence of annular groove structure on the multi-layer penetration ability. The following conclusions are obtained:

• Based on the cavity expansion model, the influence of projectile oblique penetration into the interface of multi-layer target plates was analyzed. A numerical simulation model for dynamic oblique penetration of multi-layer targets under the action of AGP and OP was established, and the motion trajectories of two types of projectiles in the target were obtained.

• During the penetration process, AGP decays faster than OP and is subjected to higher peak overload. AGP angular velocity and axis deflection angle have smaller variations. The radial offset of AGP is smaller and increases with the increase of initial invasion angle.

• The multi-layer target interface has a certain impact on the longitudinal penetration depth of AGP. The impact of the projectile groove is more significant every time it passes through a layer of interface. After the AGP moves inside the target, some of the target materials are squeezed into the groove, resulting in less rebound of the projectile.

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