Effect of groove structure on penetration performance of annular grooved projectiles impacting metal targets

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Abstract. With the continual development of advanced ammunition, a study on the effect of groove geometry on penetration performance is conducted. Based on ogive nose, an annular grooved projectile (AGP) was proposed and can generally be divided into two types (groove A and B) when considered the transition ways between groove and projectile nose. Difference in groove structures result in various penetration performance. According to dynamic cavity expansion theory and FEM simulation, the nose shape coefficient \( N^* \), depth of penetration (DOP) and acceleration curves were analysed comparatively. The results also indicated that the firm embedded behaviour of groove B nose projectile is mainly due to the filling-material in the groove rather than the friction on contact surface, unlike traditional nose shape. Furthermore, a good agreement in calculation and simulation proved the analysis method was reasonable and feasible, and would have application potential in new concept warheads.

1. Introduction

In recent years, semi-armor-piercing high-explosive incendiaries (SAPHEIs) with delayed reactions have become important for reacting to various threats, including light armor aircraft, vehicles, and general support equipment [1]. The growing development increases the need for multipurpose SAPHEI concepts. Their penetration ability is mainly influenced by three approaches [2]: impact velocity, material property and projectile nose shape [3]. Under the bottleneck of existing technology and materials [4], geometrical optimization becomes an effective way on improvement [5].

Dynamic cavity expansion theory is verified by numerous experiments as a basis for evaluating the optimization [6]. Forrestal et al [7] established an empirical equation to estimate the penetration resistance. Jones et al [8] defined a related dimensionless constant names nose shape coefficient \( N^* \) and obtained an optimal single-curve nose shape with the minimum \( N^* \). However, most efforts were mainly focused on single-curve geometry and its optimization while few work considered the rebounding phenomenon [9]. When impacting metal targets with low velocity, projectile with traditional nose shape is prone to rebound due to insufficient friction [10]. This phenomenon is unfavorable for explosive-filled projectile with delayed fuse and other applications.

Annular grooved projectile (AGP), refers to a projectile that contains one or more annular grooves in its nose. In this study, this projectile was proposed to solve the above problem, and was designed basing on a ogive shape and contained only one annular groove to simplify the analysis. Considered the different transition ways (whether smooth connections) between structures, AGP can be generally divided into two types, which are shown in Figure 1.

This paper describes two projectile types with different grooved structures comparatively. Numerical
simulations were performed using LS-DYNA software. Then the effects due to different geometries of groove on penetration performance are discussed. Consequently, groove A nose shows a superiority of DOP while groove B nose exhibits an embedded behavior in penetration.

Figure 1. Shapes of two types annular grooved projectile: Groove A /B nose and corresponding ogive nose (from left to right).

Figure 2. Side outline of an arbitrary nose.

2. Design of annular groove nose and related calculations

Assumed a non-deformable projectile having an arbitrary nose shape, as shown in Figure 2, impacts a target normally at velocity \( V_0 \) and proceeds to penetrate the target medium at a rigid-body velocity \( V \). Dynamic cavity-expansion analysis yields the following relation between the normal compressive stress \( \sigma_n \), and the projectile nose and normal expansion velocity \( v \) [11]:

\[
\sigma_n = AY + B\rho v^2
\]

where \( Y \) and \( \rho \) are the yielding stress and density of the target material, respectively. \( A \) and \( B \) are dimensionless material constants. The particle velocity at the nose–target interface is \( v = V \cos \theta \). The tangential stress on the nose was assumed to be determined by the frictional resistance on the interface:

\[
\sigma_t = \mu_m \sigma_n,
\]

where \( \mu_m \) is the sliding friction coefficient upon impact. The resulting axial resistant force on the projectile nose can be integrated from the normal compressive and tangential stresses. Thus,

\[
F = \pi a^2 \left( AYN_1 + B\rho V^2 N_2 \right)
\]

where \( a \) is the radius of the projectile shank. \( N_1, N_2 \) are two dimensionless parameters relating to the nose shape and friction. If the nose shape can be represented by the function \( y = y(x) \) for an arbitrary nose shape, as shown in Figure 2, then

\[
N_2 = N^* + \frac{4\mu_m \int_{-\infty}^\infty \cos^2 \theta \sin \theta \, dA}{\pi d^2}
\]

\[
N^* = \frac{2}{a^2} \int_0^a \frac{y}{y^2 + a^2} \, dy
\]

The nose shape factor \( N^* \) is a dimensionless number and is only related to the geometrical nose shape [10]. It quantitatively characterizes the nose shape and can be used as a quantity for evaluating the inertial resistance acting on the projectile during penetration.

Ogive nose as a common nose shape, its calibre radius head (CRH) is generally between 3 and 5 in engineering practice [2]. In this case, the AGP in this study were optimally designed based on CRH 3 and 5 ogive nose. Assume that the nose shape can be represented by the function \( y = y(x) \). This curve is usually monotonically increasing such as ogive or cone shape. However, when describing a segmented nose shape, such as annular grooved nose, there would be a decrease situation in \( y(x) \). AGP can generally be divided into three parts and the details are exhibited in Figure 3.
Figures 3. Differences between modified and original projectiles. (a) Groove A nose and (b) Groove B nose.

Part 1 (OBG) is similar to a CRH 5 ogive nose. This part needs to have enough strength to keep better stability during penetration when considering non-ideal initial condition [12]. Therefore, the groove starts from the region where \( x/b = 0.3 \) (OB). Part 2 (GBDI) is optimized by a circular arc and its length is controlled by the former and latter parts. The difference between groove A and B nose is also started from this part. Part 3 (IDEF) of groove A is based on a CRH 3 ogive nose, while that of groove B nose is based on a CRH 5 ogive nose.

Take the groove A nose for example. Design of tangent in groove A nose is to avoid the stress concentration. OEFHG encloses the modified nose wherein OBG represents part 1, GBDI represents part 2, and IDEF represents part 3. AGF and OHF represents the shape of CRH 5 and CRH 3 respectively. GH shows the circular arc of the groove and GI is paralleled to \( x \)-coordinate. Dot \( H \) and \( F \) are points of tangency. For the modified shape, \( y_{OG}, y_{GI} \) and \( y_{IF} \) are the curves of segment OG, GI and IF respectively. According to the principle of subsection integral, the nose coefficients \( N^* \) can be added together form these three parts, as given by equation (5):

\[
N^* = N_1^* + N_2^* + N_3^*
\]

\[
= \frac{2}{a^2} \left( \int_0^1 \frac{y_{OG}^3}{1+y_{OG}^2} \, dx + \int_{s_y}^1 \frac{y_{GI}^3}{1+y_{GI}^2} \, dx + \int_{s_y}^1 \frac{y_{IF}^3}{1+y_{IF}^2} \, dx \right)
\]

As a groove structure, the curve of GI segment contains a decreasing function segment, which means that the derivative of the \( y_{GI} \) could be negative. Considering the limitations of classical cavity expansion theory, corresponding simplified outlines instead of actual outlines were used in calculation. Figure 4 presents the relationship of \( N^* \) about four types of noses. The \( x \)-coordinate is based on CRH 3 ogive nose.

Figures 4. The relationship between \( N^* \) of the four projectiles types and nose position.

Figure 5. Dimensions of four types of projectiles (mm).

3. Materials and methods
The annular grooved projectiles (AGPs) used in this study are designed based on ogive shape. The significance of the groove structure is to obtain a relatively superior performance in penetration. Dimensions of four kinds of projectiles are shown in Figure 5 and the length of projectile shank was 3 times its diameter. Rounded structures at both ends of the groove and chamfer of the tip were designed to avoid stress concentration.

In this study, all of the targets were 30 mm thick and 100 mm in radius. They were made of the 45 steel. As a ductile metal, this material has an ultimate tensile strength of 496 MPa [13]. Furthermore, the projectile was fabricated from a high-strength material, i.e. the 30CrMnSiNi2A steel having the ultimate tensile strength of 1767 MPa [14]. These hardened steel projectiles experienced negligible inelastic deformation during the impact process and consequently can be considered as ‘rigid body’ [15]. To simplify the analysis, the coefficient of dynamic friction between the projectile and the target was also assumed to be a constant.

LS-DYNA was used for the simulations. The symmetry in the problem was exploited by modelling only half the projectile and the plate. To reduce the computation time, the refined shell elements were used, as shown in Figure 6. The mesh comprised 8-node brick elements with reduced integration and stiffness-based hourglass control with exact volume integration. Element size of the projectile was 0.5×0.5×0.5 mm³ while that of target (the impact region) was 0.2×0.2×0.2 mm³. Outside of the impact region, the mesh became bigger radially towards target edge. Contact between different parts of the model was modeled using an eroding single surface segment-based formulation [16]. The target was modeled using a modified version of Johnson-Cook constitutive material model [17]. The main material parameters used in the simulation are listed in Table 1. Moreover, the target was fully clamped at the boundary.

![Finite element mesh of AGP impacting a metallic target.](image)

**Table 1.** Main parameters for J-C constitutive relations of target material [13].

| A/(MPa) | B/(MPa) | C | n   | m   | T_c / (K) | T_a / (K) | ρ / (kg/m³) | E/(GPa) | D_1   | D_2   |
|---------|---------|---|-----|-----|-----------|-----------|-------------|---------|-------|-------|
| 496     | 434     | 0.07 | 0.307 | 0.804 | 293       | 1763      | 7800        | 210     | 0.636 | 1.936 |

4. **Numerical simulation results and discussion**

Numerical simulations of four types projectiles were carried out under the same initial conditions. All of the impact velocities were under the ballistic limits to prevent perforating. In this case the penetration process can generally be divided into two phases: forward phase and rebound phase. The former indicates the process before the projectile reaches the maximum DOP, while the latter represents the remaining penetration process until the projectile is no longer moving. As a result, the performance of projectiles in these two phases could exhibit different penetrating performance.

4.1. **Superiority of DOP in forward phase**

Three velocities were selected for the simulation and the variation of deceleration, velocity and DOP of those projectiles were analysed. Figure 7 shows the deceleration time-history curves of four types of
projectiles. In general, the groove A nose projectile has a smaller peak deceleration value and a wider pulse, whereas the CRH 3 ogive nose projectile has the largest peak. It indicates that the groove A has small penetration resistance and long penetration time which benefits the DOP. The vertical dashed line in this figure represents the moment when groove structure contacted target. Before this moment, three types projectiles except the CRH 3 one had the same deceleration value due to the same outline in Part 1 (Figure 3). However, only the curve of groove B nose projectiles increases sharply after this moment and becomes negative after reaching zero.

![Figure 7](image_url)

**Figure 7.** The deceleration time-history curves at different impact velocities. (a) 250 m/s, (b) 300 m/s and (c) 350 m/s.

Since the process of AGP vibrates in the target is much longer than that of penetrate, only the first 300 μs data was displayed and ignored the subsequent lengthy vibration curve segments. Figure 8 exhibits the corresponding velocity time-history curves of those projectiles. The vertical dotted line and the curve tendency are similar to that of deceleration curve. Different from other nose shapes, only groove B nose projectiles obtain a rebound velocity that approaching zero obviously.

![Figure 8](image_url)

**Figure 8.** The velocity time-history curves at different impact velocities. (a) 250 m/s, (b) 300 m/s and (c) 350 m/s.

The curves shown in Figure 9 clearly reflect the effect of groove geometry on penetration performance. Considered the coefficient $N^*$ and $k$, the DOP of CRH 3 projectiles generally 20% ~ 30% lower than that of CRH 5 projectiles. Furthermore, two groove geometries show visible difference with an increasing impact velocity: the groove A projectile exhibits a superiority of DOP under low-velocity impact, especially when the dimensionless DOP is less than 2. This phenomenon could be explained though the coefficient $N^*$. 

![Figure 9](image_url)
4.2. Superiority of embedment in rebound phase

The embedding phenomenon of projectile was studied in rebound phase. Due to elastic recovery of target material [15], projectile has a rebound tendency after reaching maximum DOP. This phenomenon would cause projectile rebounded from the target, which is unfavourable for explosive-filled projectile with delayed fuse.

Figure 10 shows the penetration process of three types projectiles impacting 30 mm steel plates at 300 m/s respectively. Some typical physical behaviour of targets were well-captured in the numerical simulation, such as petals and denting on the impact surface. Three moments, which represented three typical relative positions between groove and target were selected. The CRH 5 ogive projectile as a comparison, exhibits that the target material is flowing along the projectile contour. This phenomenon is different from annular groove projectile. Regardless of groove A or B noses, the target material does not flow along the contour of groove in the initial stage which caused a cavity in the groove.
With DOP increased, target material is squeezed and filled into the groove structure contributed by region HI (in Figure 3(b)) of groove B nose, while the cavity in groove A nose has not been filled until the end.

The groove-filling processes of groove B nose are shown in Figure 11 to obtain more detailed deformation in penetration. After reaching the maximum DOP, projectile has a rebound tendency and a long-term vibration due to the elastic recovery of target [17]. In the case that projectile successfully prevented rebounding in the first vibration, it would embed into target. For ogive projectile, the resistance only comes from friction between projectile and target is generally unstable and may not be sufficient to limit the rebounding.

![Figure 11. Penetration process of the groove B nose projectile.](image)

However, groove B provides another relatively stable embedded method based on the plastic deformation of filling-material in the groove. According to simulation results, groove B projectile has a embedding superiority in rebound phase. Furthermore, compared to other nose shapes, this superiority of groove B indicated that the firmly embedding behaviour was mainly due to plastic deformation of the filling-material rather than friction between the projectile and target.

5. Conclusions
The effect of groove geometries on impacting metal targets was studied. Based on the experimental and numerical observations, the conclusions are written as follows:

- compared with traditional ogive projectile, the annular grooved projectiles were proposed and exhibited DOP superiority or embedded behaviour with different groove structure.
- influence of the nose shape coefficient $N^*$ of annular grooved projectile on penetration performance was discussed based on calculation and simulation results.
- groove A projectile has a deeper DOP than corresponding ogive projectile during low speed impact. As impact velocity decreases, this superiority caused by nose shape becomes more significant.
- groove B projectile has a firm embedded behaviour during low-velocity impact. This behaviour is mainly due to the plastic deformation of filling-material rather than friction between the projectile and target.

However, the effect of groove geometry is complex and is influenced by the target material, groove size, target thickness, and impact velocity. Therefore, further theoretical and experimental researches have to be carried out to support the findings in this study. It is hoped that this framework will effectively optimize the design of complex nose details to achieve a variety of penetration performance.
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