Numerical Analysis of Nylon Projectile Engraving into Rifle

Yucai Dong, Jing Sun, Liming Gong, Jianjun Wang
Xi'an Branch, China Academy of Space Technology, Xi'an, 710100, China
kingdongyufeng@163.com, sunjing12@163.com, glming@163.com, wjj21985@126.com

Abstract. The parametric model of projectile and rifled barrel is established by using finite element software ABAQUS. The numerical simulation of the projectile engraving into the bearing band under the maximum chamber pressure of 10 MPa and 15 MPa is carried out respectively. The force condition and morphological changes of projectile during extrusion at different times are analyzed and explained. The variation of velocity and displacement of projectile is obtained in the chamber, respectively. Simultaneously, the velocity and displacement components of rifled barrel and slippery barrel after muzzle exit are presented. It is verified that the rifling structure can effectively reduce the emission dispersion of the launching system under gravity free.

1. Introduction
Under the collision and extrusion of the rifling and connecting conical chamber, the rifling material firstly produces elastic deformation, followed by plastic deformation, and finally is etched by the rifling. That is, the process of engraving the bearing band[1-4]. The projectile is not in motion during the elastic deformation phase. When the bottom pressure causes the rifling material to contact the starting point of the rifling, the yield limit is first reached, and the rifling begins to engraving into the connecting conical chamber. As the movement of the projectile increases, the amount of plastic deformation increases, and the deformation resistance also increases. The projectile accelerates under the action of the bottom pressure and the extrusion resistance. With the occurrence of engraving, the deformation of the bearing band material and the high temperature generated by the friction between the bearing band and the rifled barrel cause the material to be softened, causing the material properties to become unstable and the deformation to be intensified. As the projectile moves inward again, since the elastic band has been completely embedded in the rifled barrel, its plastic deformation is small, and the engraving resistance is gradually reduced. The final resistance is basically composed of the force of the bearing band and the rifling and the gun tube to stabilize. The internal structure of the gun tube is complicated and the load is deteriorated. The finite element method can be used to calculate the stress and strain of the barrel during the launch of the gun. In this paper, using ABAQUS finite element analysis software, through the application of load and restraint to the gun tube model, the motion simulation analysis of the engraving process of a 25mm aperture projectile is carried out.

2. The characteristic data of internal ballistics calculation
Stress analysis is shown in Figure 1. \( P \) is the tail pressure, which is approximately the same as the pressure on the tail section. \( F_p \) is the pressing resistance, \( F_p = P_L \pi d L \mu \). In the formula, \( P \) is the squeeze pressure, can be approximated as equal to the chamber pressure P.L is the contact length, \( \mu \) is the coefficient of friction. When the projectile and the body tube are in clearance, the friction coefficient is taken as 0.01. \( l_0 \) is the distance from the tail of the projectile to the bottom of the
chamber after the projectile is filled in place, $x$ is the projectile stroke. $A = \pi d^2/4$. Assuming the mass of the projectile to be $m$, $m = 16.1$ g. The volume of the chamber is $V_0$, $V_0 = 0.85$L. The cavity volume is formed by the gas chamber and the tail is $0.027$L. The diameter $d$ of the internal diameter of the projectile along the moving part of the projectile is $25$mm. The cross-sectional area of the segment is set to $A$.

The work of the whole system is derived from the internal energy of the working gas, and the internal energy change is macroscopically expressed as the change of the gas temperature. In order to facilitate analysis, the gas in chamber can still be regarded as ideal gas here.

$$P_0V_0 = P(V_0 + V_k + Ax)$$

Equation (1) can easily estimate the relationship between the gas pressure in the crucible and the stroke of the projectile. As the stroke of the projectile increases, the rolling pressure begins to decrease, and the descending speed shows a decreasing trend. When the initial rolling pressure is $10$MPa, the projectile exits the muzzle instantaneously, and the chamber pressure is $5.27$MPa. When the initial rolling pressure is $15$MPa, the projectile exits the muzzle instantaneously, and the chamber pressure is $7.91$MPa.

3. The finite element model

The main rifling parameters of the barrel include number of rifling lines $n$, groove diameter $D_2$, the groove width $W$, land diameter $d_1$, and rifling lead $\lambda$. Under the requirement of unchanged overall size, choose the groove diameter as $\phi 25$, refer to the rifling parameters of similar caliber artillery and firearms, the number of rifling lines is taken as 16, the groove width is taken as $3$mm, and land diameter is taken as $\phi 24.4$. The maximum diameter of the projectile is $25$mm, the length of the projectile is $34$mm, and the weight of the projectile is $16.1$g. In order to reduce the resistance of the projectile to move in the barrel, a groove with a depth of $1$mm is left in the middle of the projectile. Combined with conventional gun projectile loading relative position, the starting position of the projectile is at the beginning of the slope to the back end. The projectile-barrel coupling three-dimensional model is shown in Figure 3.
Meshing the established 3D model with Hyper Mesh finite element pre-processing software. The barrel and the projectile are meshed C3D4 grids respectively, wherein the number of the barrel model grid is 387455, and the number of projectile grids is 44458. The three-dimensional model of the mesh is divided as shown in Figure 4. In this simulation model, the projectile is made of a certain nylon material, and the barrel material is made of gun steel (30SiMn2MoVA). The barrel is considered as a rigid body during the simulation process. Because the projectile engraving process involves large deformation and high strain of materials, the projectile material adopts the ideal elastoplastic model. The relevant parameters are shown in Table 1.

| $\rho$ (kg/m³) | Yield limit (MPa) | Tensile elastic modulus (GPa) | Shear strength (MPa) | Poisson ratio | Elongation at break (%) |
|---------------|------------------|-----------------------------|---------------------|--------------|------------------------|
| 1170          | 32               | 1.1                         | 24                  | 0.3          | 230                    |

4. Simulation analysis

The ABAQUS finite element analysis software is used to simulate the internal simulation of the simulation model. Considering that the simulation process involves large deformation of the material, set the solver to Dynamic, Explicit, and open the geometric nonlinear solution mode. After the calculation is completed, the velocity and displacement of the projectile are extracted and analyzed.

4.1. Projectile deformation analysis

The deformation degree of the projectiles is analyzed at different times. When the rifling is just squeezed into the rifling, the stress at the position of the center of the projectile is larger, and the front part of the projectile forms a corresponding nick. With the Advancement of the projectile, the front bourrelet completely squeezed into the rifling, and the rear bourrelet began to squeeze into the rifling. At this time, the stress of the rear bourrelet became larger. After the projectile is completely squeezed into the rifling, the front and rear bourrelet etching formation and the stress distribution in the front and rear centering portions is relatively uniform. It can be seen from the deformation of the projectile during the movement of the crucible that the strength of the projectile meets the requirements of the movement within the crucible.
4.2. Analysis of the motion of the projectile under the pressure of 10MPa

When the internal pressure was applied to the bottom of the projectile, the maximum pressure of 10 MPa was applied, and the velocity and displacement of the projectile were extracted after the simulation. The dynamic friction coefficient of nylon material and steel is 0.01.

![Figure6. Projectile displacement with time](image)

![Figure7. Resultant velocity of projectile with time](image)

It can be seen from Fig. 6 and Fig. 7 that the maximum displacement of the projectile is 1160 mm under the maximum pressure of 10 MPa. The maximum speed of the projectile is 364 m/s, the maximum speed occurs at 0.34 ms, and the displacement is 618 mm. When the projectile reaches the maximum speed, the projectile speed will decrease because the bottom pressure is less than the friction between the projectile and the barrel.

4.3. Analysis of the motion of the projectile under the pressure of 15MPa

When the internal pressure was applied to the bottom of the projectile, the maximum pressure of 15 MPa was applied, and the velocity and displacement of the projectile were extracted after the simulation. The dynamic friction coefficient of nylon material and steel is 0.01.

![Figure8. Projectile displacement with time](image)

![Figure9. Resultant velocity of projectile with time](image)

It can be seen from Fig. 8 and Fig. 9 that the maximum displacement of the projectile exceeds 1500 mm at the highest pressure of 15 MPa. The maximum speed of the projectile is 572 m/s, the maximum speed occurs at 0.35 ms, and the displacement is 1005 mm. When the projectile reaches the maximum speed, the projectile speed will decrease because the bottom pressure is less than the friction between the projectile and the barrel.

4.4. Analysis of projectile posture under two kinds of barrel

| Type of barrel   | X-direction speed /m s⁻¹ | X-direction displacement /m | Y-direction displacement /mm | Z-direction displacement /mm |
|------------------|---------------------------|----------------------------|------------------------------|------------------------------|
| 16 bands rifle   | 1169.57                   | 583.60                     | 11.23                        | 10.58                        |
| Smooth bore     | 1266.69                   | 632.03                     | 76.56                        | 74.09                        |

Table 2. Contrast comparison of projectiles without considering gravity (30Mpa)
At 30 Mpa chamber pressure, the flight attitude after launching 3ms under two barrels is as follows. The 16 bands rifle have X-direction velocity of 1169.57 m/s, X-direction displacement of 583.60 m, Y-direction displacement of 11.23 mm, and Z-direction displacement of 10.58 mm. The smooth bore has X-direction velocity of 1266.69 m/s, X-direction displacement of 632.03 m, Y-direction displacement of 76.56 mm, and Z-direction displacement of 74.09 mm. It can be seen that the launching divergence of the projectile can be effectively reduced under the condition of the rifled barrel, but at the same time, the speed of the main striking direction of the projectile will be lowered.

5. Summary
The mechanical properties of the projectile material have certain influence on the extrusion of the projectile and the movement of the ball. The model adopts the characteristics of the ideal elastoplastic material. The calculation results are not completely consistent with the actual situation. The mechanical properties of the specific material of the projectile should be determined to make simulation results more accurate.

During the movement of the projectile in the crucible, when the projectile reaches the maximum speed, because the bottom pressure is insufficient to overcome the movement resistance of the projectile, the velocity of the projectile will decrease, resulting in the velocity of the projectile being less than the maximum speed and wasting part of the energy. Therefore, by shortening the body tube, the projectile can be the maximum speed of the ballistic process when it is out of the muzzle.

By using the launching tube of the rifle, the launching dispersion can be effectively improved, and the system striking accuracy can be optimized, and a certain muzzle velocity is sacrificed compared with the smooth bore scheme, but within an acceptable range.

References
[1] Zhang X F, Lu X H. Interior ballistics of erosion guns. Beijing: National Defense Industry Press, 2001: 190—209.
[2] Xia Z G. Plastic mechanics [M]. Shanghai: Tongji University Press, 1991.
[3] Hu H B, Chen S X, Cao L J. Test and simulation of the engraving process of driving band into rifle[J]. Science Technology and Engineering, 2014; 14(31): 256—261.
[4] Fan L X, He X Y. Finite element simulation and process analysis of projectile entering into barrel[J]. Aeta Armamentar It, 2011; 32(8): 963—969.
[5] Mu L J, Hu W J, Tao J L. Research on compression mechanical properties and constitutive model of nylon[J]. China Measurement & Test, 2017; 43(11): 129—133.
[6] Wang S M, Tan H F, Luo X L. Numerical simulation and experimental study on fabric skin tearing properties of Nylon-230T/TPU [J]. Acta Materiae Compositae Sinica, 2018; 35(7): 1869—1877.