Analysis of interior ballistic performance degradation of a worn gun barrel based on finite element method

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Abstract. A comprehensive accelerated life test of a 12.7mm caliber barrel gun barrel was carried out to study the variation in interior ballistic performance during the lifespan of a large-caliber machine gun. The wear mechanism at different positions in the bore was analyzed, and the wear data for the bore was obtained from the test. On this basis, a three-dimensional barrel-wear finite element model was established using the parametric modeling method. The variation law of interior ballistic performance and the influence of wear location on ballistic performance were studied. The results showed that, after shooting 4300 rounds, the radial swing of the projectile head at the muzzle reached 0.35 mm and the projectile rotational speed decreased by 57.5% compared with the unworn performance. In addition, the wear on the initial position of the rifling not only caused the swing of projectile in the barrel, but also aggravated the wear of other parts of the inner wall. The wear at the muzzle had a more obvious effect on the rotational speed of the projectile. Finally, it was concluded that the fundamental reason for interior ballistic performance degradation was wear on the initial position of the rifling.

1. Introduction

The function of the barrel is to act in conjunction with the propellant gas to give a projectile a certain initial velocity and ensure a stable rotational speed for the projectile in flight. Erosion-wear is a key factor that restricts the performance of a projectile weapon with an integral barrel and, if controlled, can prolong its service lifespan. Establishing the relationship between barrel wear and various indices of interior ballistic performance is of great significance in the study of the degradation mechanisms, which affect interior ballistic performance and can lead to improved barrel lifespan.

In recent years, in order to improve the performance and combat lifespan of the barrel, researchers have done a lot of meaningful work through experimentation and simulation. Despite a large amount of research performed in terms of shooting experiments, few public articles have been published due to such reasons as confidentiality. Engineering experiments that highlight certain rules provide good practical guidance. The projectile and the driving band engraving process performed by the barrel bore plays a vital role in determining the ballistic performance and projectile stability. Therefore, a large number of engineering experiments have been directed at this process. Joseph South [1] et al. studied the extrusion force and projectile deformation of 5.56 mm caliber projectiles using rate-controlled push tests. Bin Wu [2] et al. used an electronic universal testing machine and a specially designed gas-gun-based dynamic impact test rig to analyze the process of strip extrusion of different materials.
during firing. The experiments show that the strain rate and contact temperature of the strip have a significant influence. Tony D. Andrews [3] used strain gauges to measure the effect of the projectile driving band on the barrel and analyzed the problem of fatigue damage caused by the stress applied to the front of the barrel by the driving band.

Computer-aided engineering (CAE) technology, especially finite element numerical simulation, has become an effective and feasible research method and an essential tool for solving difficult measurement-based experiments and transient reaction phenomena. Firstly, CAE technology can provide guidance in the production and processing of barrels and projectiles. Some prior literature [4-6] has presented numerical simulation models for the material properties of the barrel, the design and manufacture of the projectile, and the position of the projectile to optimize production. Secondly, CAE technology can also achieve the effect derived from experimentation, to realize the study of the processes involved as projectiles squeeze through the barrel. Studies have shown that [7, 8] the driving band structure, the driving band material, the size of the rifle, and the diameter and quality of the projectile all affect the extrusion process. For electronic components inside a guided projectile, dynamic reliability during extrusion must also be guaranteed [9]. J. South et al. [10] and Zhen Li et al. [11] used finite element simulation technology to evaluate the calculation methods used in the extrusion process. Thirdly, for the data that cannot be obtained through experimentation, the finite element simulation method based on theoretical analysis is a good complementary solution to the problem. In the literature [12, 13], the combustion characteristics of gunpowder in the barrel and the temperature rise in the barrel caused by the high-temperature gunpowder explosion were studied in detail to determine the thermal stress experienced by a gun barrel during firing. For small-caliber pistols, S. Deng et al. [14, 15] performed finite element simulation on the motion of the projectile in the barrel bore. The model accurately reflected the rotation, nicking, and stress of the projectile. In addition, the rifle type [16] and the structure [17, 18] had a significant influence on the force and the projectile’s motion and orientation in the barrel bore. Finally, considering the influence of the plastic yielding effect of the barrel material [19] and the loss of the effectiveness factor due to the fracture of the elastic driving band [20], typical damage mechanisms of internal ballistics can be analyzed.

At present, the establishment of a scientific, efficient evaluation index for gun barrel ballistics in order to improve the service lifespan is a more concerning issue. As the number of projectiles being fired increases, the structural size of the barrel changes significantly due to erosion and wear. A large number of previous studies focused on the mechanisms of erosion and wear [21-25], while research into the impact of erosion and wear on ballistic performance is relatively rare. Chenli Tao [26] et al. have shown that the interior ballistic peak phenomenon of small-caliber gun barrels after erosion and wear was related to the mismatch between the structure of the barrel and the size of the projectile belt. Chuanjun Ding [27] et al. proposed a mesh generation method for modeling gun barrel wear, which improved the efficiency of different established barrel structural models and verified the wear effects of pressure and initial velocity of the projectile on the gun barrel.

The interior ballistic performance degradation mechanisms of barrel erosion and wear, such as the projectile’s motion and orientation in the bore, and the velocity and rotational speed of the projectile, are of great significance for improving inherent defects in the barrel and assisting engineers in designing and developing new types of rapid-fire weapons. In this study, the projectile-barrel coupling model for different periods of wear is established, based on the idea of parametric modeling in combination with standard shooting experiments. The interior ballistic performance degradation mechanisms for large-caliber machine-gun barrels are analyzed in terms of the force exerted on the inner wall of the barrel, the projectile’s motion and orientation, and the rotational speed and muzzle velocity of the projectile through the barrel. Meanwhile, specific analysis on the effects of wear on the interior ballistic performance was carried out in terms of the comparative analysis of mouth and tail wear and actual wear of the barrel, respectively, revealing the root causes of the barrel’s lifespan limitations.
2. Accelerated life test
An accelerated life test on a 12.7 mm machine gun has been carried out using the standard firing code [28]. Fig. 1 is a sectional-view sketch of the barrel structure. The rifling starting point was defined as the rear part of barrel and the outlet of barrel was defined as the front part. The change in the bore land diameter in the gun barrel was measured using different caliber gauges, and the depth of entry of each gauge was recorded. Diameter distributions (Fig. 2) along the barrel body were shown at different shooting stages. As shown in Fig. 3, the barrel rear part has relatively high diameters at end-of-life stage. This is believed to have been caused by severe wear owing to the instantaneous high temperature, erosion of the gunpowder gas caused by high pressure, and the extrusion action of the projectile. In addition, an accelerated wear phenomenon was observed at the muzzle with an increase in the number of shots, and the land lines were almost flattened (barrel length: 800 mm).

3. Interior ballistic modeling
3.1. Structural model
Based on the bore diameter distribution data from life test, the worn barrel is achieved using a parametric modeling method with the help of the Python language. Specific steps are as follows: 1)
According to the wear data, the cross section nodes of the rear part are established; 2) For the wear section with the same opening slope, according to the slope of the section, the rotating-stretching model of the joints is established based on the spiral angle of rifle; 3) For the area without wear, the nodes are rotated-stretched directly to the corresponding length. The finalized structural model is given by Fig. 4. The size in the figure refers to the diameter of the gun (between the lands) at the starting position of the rifling, and the bore diameter in the axial direction of the barrel is varying with the data. Meanwhile, the projectile structure is generated based on the HyperMesh software, as shown in Fig. 5. The mesh models are assembled in ABAQUS/ EXPLICIT software. In this study, the element type C3D8R is chosen for both the gun barrel and the projectile.

3.2. Material properties

The barrel material is high-strength steel, the projectile shell is copper, and the core of the projectile is steel. Table 1 shows the mechanical properties of the relevant materials. There are a series of complex nonlinear mechanical phenomena in the process of contact between the projectile and the barrel material, such as temperature rise and stress softening. The temperature rise will cause the change of bore size. However, it is much smaller than the change of the inner wall size caused by wear. Besides, the projectile shell is very thin, the effect of stress softening is not obvious. To this end, the thermal stress and the heat generated by contact friction are ignored in the model. In the computation, von Mises plasticity with isotropic hardening without strain rate effects was assumed [7].
### Table 1. Mechanical properties of the gun barrel and projectile.

| Material type | Elastic modulus/GPa | Shear modulus/GPa | Density/(kg·m⁻³) | Poisson's ratio | Yield stress/MPa |
|---------------|---------------------|-------------------|------------------|----------------|-----------------|
| Barrel steel  | 206                 | 80                | 7850             | 0.29           | 933             |
| Copper        | 108                 | 44                | 8800             | 0.35           | 115             |
| Steel         | 210                 | 79                | 7850             | 0.29           | 352             |

3.3. **Load**

Gravity is added to the projectile throughout the internal ballistic period. The internal ballistic period includes phenomena such as gunpowder burning, energy conversion, and projectile movement. The variation rule for the breech pressure can be determined by the classical internal ballistic equation [9, 29]. Based on the classical internal ballistic equations, the internal ballistic calculation is programed in FORTRAN, and the fourth-order Runge-Kutta method is used to solve the internal ballistic differential equations.

3.4. **Contact**

The friction coefficient between metals is related to relative velocity $v$ and pressure $\sigma_f$, and decreases with the product of relative velocity and increasing pressure. In the friction process, metal melting may occur, which changes the lubrication mechanisms between the metals. The experimental results for the U.S. Military presented in reference [30], as the speed of the projectile increases rapidly within the barrel, the dynamic friction coefficient is set as 0.1 [15].

4. **Effect on interior ballistic performance**

4.1. **Posture of the projectile squeezed into the gun**

Before the firing test, there is almost no gap between the inner wall and the projectile surface. When the number of shots reaches 4300 rounds, a gap of approximately 0.6 mm on one side is created at the four cones where the projectile is positioned, as shown in Fig. 6. Due to the increase in barrel rear part caused by barrel ablation wear, the projectile loses its ideal orientation, and the center of the projectile no longer coincides with that of the barrel. Therefore, as the wear of the barrel increases, the initial contact area between the projectile and rifle changes when the projectile is squeezed into the barrel, resulting in uneven marks on the projectile, and a decrease in symmetry and roundness.

![Figure 6. The moment when the projectile squeezed into the barrel: (a) unworn state; (b) end-of-life state.][28]

4.2. **Projectile motion in the bore**

The horizontal and vertical displacement curves of the projectile head were obtained as the projectile moved along the barrel, as shown in Fig. 7 and Fig. 8. Due to the moderate reductions in size of the projectile and barrel, the projectile fluctuated in the vertical direction. At the same time, due to the rotation of the projectile in the bore, the fluctuation in the vertical direction was transmitted to the horizontal direction and the fluctuation amplitude in the horizontal direction increased gradually. When the projectile was ejected from the chamber, the vertical swing amplitude of the head increased from 0.008 mm at 1200 rounds to 0.35 mm at 4300 rounds. The maximum swing displacement of the
projectile head in the horizontal direction was 0.032 mm for the different shooting stages, which is much smaller than that in the vertical direction.

Figure 7. Vertical displacement of the projectile head.

Figure 8. Horizontal displacement of the projectile head.

4.3. Projectile muzzle velocity $v$ and muzzle rotational speed $\omega$

The velocity-time curve is shown in Fig. 9. Although the degree of barrel wear in the four shooting stages was different, the acceleration trend of the projectile in the barrel was basically the same. The muzzle velocity at each stage of the accelerated life test was measured. 10 rounds were measured each time, and the average value was calculated. The initial muzzle velocity for the accelerated life test increased slightly in the early stages, but the overall change showed a downward trend. This trend was relatively stable in the early stages, and a steep decline occurred towards the end of its lifespan. The simulation results were in good agreement with the experimental data, and the maximum relative error was only 1.27%. The accuracy of the model was verified, as shown in Fig. 10. The initial muzzle velocity of the projectile was 807 m/s. When the number of shots reached 4300 rounds, the muzzle velocity of the projectile was 765 m/s, showing a decrease of 5.2%.

Figure 9. Velocity-time curve of the projectile.

Figure 10. Muzzle velocity of the projectile.

The rotational speed-time curve is shown in Fig. 11. As the number of shots increases, the acceleration of the projectile rotational speed slows down significantly. When good contact is made between the projectile and the rifling, the muzzle rotational speed of projectile is related to the angle of the rifling $\beta$, and $\omega = v \cdot \tan \beta / r$, where $r$ is the radius of projectile. The calculated muzzle rotational speed based on the muzzle velocity of the projectile is shown in the black curve in Fig. 12, assuming that the projectile and rifle bore are making good contact with each other. The actual simulation results showed that the muzzle rotational speed of the projectile on exit decreased significantly with increasing wear, as shown in the red curve in Fig. 12. It indicates that the projectile did not fit closely within the rifle when it was moving through the bore. When the number of shots fired reached 4300
rounds, the muzzle rotational speed was 3480.5 rad/s, which was 57.5% lower than that of the barrel without wear.

4.4. Effect of wear position
The rear part and front part of the barrel show obvious wear after shooting a certain number of rounds. Through the analysis of Section 4.1, it can be seen that the wear on the rear part will aggravate the wear on front part. The actual wear at both ends of the barrel is thus interrelated. By means of parametric modeling, the wear models for the rear and front part can be established respectively, so as to quantify the specific impact of different wear positions on interior ballistic performance.

Based on the actual wear data, a comparative analysis of barrels using three wear states, actual wear, rear wear and front wear, was carried out. Fig. 13 shows the vertical displacement of the projectile head at different stages of firing. The projectile has a significant swing when moving in a barrel with only rear wear. Since the front part is not worn, the swing of the projectile is suppressed. When the bore was only worn in the front part, the projectile did not show significant swing. This is because the impact of gravity on the projectile is negligible over the length of the barrel in the case of good restraint at the beginning of the rifling. Therefore, the initial movement of the projectile caused by the rear wear of the bore is the fundamental reason for the swing of the projectile in the barrel.
5. Conclusions

(1) A projectile loses its orientation after being separated from the shell when the radial restraint is reduced due to it moving in a worn barrel, resulting in collision between the projectile and the inner bore. The collision results in uneven contact stress on the inner wall of the barrel, uneven wear on the inner bore due to the action of the projectile, and subsequent drum-shaped deformation of the inner bore. The uneven contact stress also increases with an increasing degree of wear on the rear part of the barrel, which accelerates the wear on the front part.

(2) Due to the influence of barrel wear, the vertical displacement of the projectile head increased from 0.0085 mm at 1200 rounds, to 0.3536 mm at 4300 rounds. The muzzle velocity $v$ and muzzle rotational speed $\omega$ of the projectile were 764.6 m/s and 3480.5 rad/s, respectively, which were 5.3% and 57.5% lower than that of the barrel without wear, respectively. Therefore, it is concluded that the deviation of the projectile's exit attitude and the significant decrease in the projectile's rotational speed are the main mechanisms governing the degradation of interior ballistic performance.

(3) The rear wear of the barrel was the main cause of the swing of the projectile in the bore, which affected the attitude of the projectile. The front barrel wear had a more significant effect on the rotational speed of the projectile, which reduced the stability of the projectile once it left the barrel. In summary, the wear on the rear part of the barrel (the initial position of the rifling) was the fundamental cause of the end of barrel life.

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