Finite element analysis of the friction and wear of the barrel bore during the projectile extrusion

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Abstract. The size change of the forcing cone directly affects the ballistic performance of the gun and the life of the gun barrel. In order to study the force law and wear law of the forcing cone during the continuous engraving process of the projectile, which established a refined finite element model of the projectile-barrel interaction. The model contains rifling finite element mesh grid with process chamfer. Based on the established transient coupled thermo-mechanical finite element (FE) model of the projectile-barrel interaction, the effects of the temperature and pressure of the gunpowder gas, the friction coefficient between the rotating band and the forcing cone were comprehensively considered. Combined with the Archard wear model, numerical method are used to obtain the stress law of the forcing cone and the amount of wear due to friction in the continuous engraving process of the projectile. The research content in this article can provide some guidance for predicting the life of the tube.

1. Introduction
During the firing of the artillery, the gun barrel is a very complex component subject to force. Under the high-temperature, high-pressure, high-speed gunpowder gas and the plastic deformation of the rotating band, the pressure in the body changes sharply and the driving side force of the rotating band is repeatedly affected. which caused the shape and size of the forcing cone are gradually damaged. the forcing cone is the most severely wear and worn part of the gun barrel, which can cause rapid changes in the ballistic performance and the life of the barrel. During the process of engraving, the rotating band squeezed into the forcing cone, and then cut by the rifling. The speed can reach tens of meters per second, and the friction between the rotating band and the rifling has the characteristics of high speed and high contact pressure. With the increase in the number of projectiles, the stress on the slope bore became worse and the wear became more severe. At present, there are few reports on the stress and wear of the gun barrel bore. Bin Wu et al [1,2,3] researched the interaction of copper and nylon rotating bands with a CrNiMo gun steel during engraving under quasi-static and dynamic loading conditions. Lu Ye et al [4] studied the influence of the forcing cone angles on the stress of barrel...
forcing cone, the three-dimensional finite element models of barrel and projectile at different forcing cone angles are established, in which contains the structures of barrel and projectile, and nonlinear constitutive relations are considered. The effects of different forcing cone angles on the projectile engraving process are analyzed. Sun et al [5] researched the dynamic engraving process of the rotating band is studied through numerical simulation, and the maximum resistance, engraving pressure and projectile velocity at the corresponding time are obtained. The deformation and groove formation processes of the rotating band are analyzed. The dynamic engraving resistance of the rotating band, the engraving pressure and movement of projectile are also calculated. Ding [6] presented a modeling method of the gun barrel and a meshing strategy about FE model of the worn barrel, and analyzed about the influence of the wear of gun barrel on the interior ballistics performance. In the field of gun barrel wear. Miodrag Lisov [7] through theoretical and experimental observations studied the friction mechanism between the rotating band and gun barrel. The friction mechanism is considered to be related to the internal ballistic factors, materials factors, and the friction coefficient of the rotating band and gun barrel. The numerical calculations verify the proposed friction model is basically consistent with the test results. Stiffler A K [8] calculated the friction coefficient of the rotating band melted liquid film through fluid dynamic. Heikki Keinanen et al [9,10] through experiments and numerical simulations to study the engraving process of the rotating band, it was pointed out that the contact pressure between the rotating band and the gun barrel greatly affected the friction during engraving process. Lisov [11] considered the friction coefficient between the rotating band and gun barrel is a function of the positive pressure and relative speed. Miao Li et al [12] researched the dynamic characteristic of rotating band engraving process are greatly affected by the friction behavior between the rotating band and barrel. A new temperature dependent friction stress model is introduced to calculate the friction behavior between the rotating band and barrel.

In summary, many scholars have done a lot of research on the theoretical and numerical calculations of the projectile engraving into the forcing cone, but less research has been done on the force state and friction and wear state of the forcing cone, In addition, the finite element model of the rifling did not take into account the process chamfering, which caused the finite element model of projectile-barrel interaction did not agree with the actual results to some extent. Therefore, based on previous research, the author established a finite element grid model of the forcing cone considering the process chamfer, and also established a finite element model of the projectile-barrel interaction, The model takes into account the effects of temperature and pressure generated by the burning of the powder on the extrusion process; the friction coefficient between the rotating band and the gun barrel as a function of temperature and pressure is considered. In the process of the rotating band being squeezed into the forcing cone, the force of the forcing cone and the friction and wear law of the forcing cone under continuous shooting environment were studied in detail.

2. Transient coupled thermo-mechanical of projectile-barrel interaction

2.1. The finite element model

Taking a middle-caliber naval gun body tube as the research object, the initial structure of the barrel bore of the barrel was taken from the complete barrel (including the taper of the forcing cone, male
and female rifling with process chamfering), The finite element grid model of this part and the projectile are established respectively, and the mesh is divided by the C3D8RT element. In FM model, the rotating band and the body are bound by nodes to simulate the assembly relationship between the rotating band and the body. The rotating band and the bourrelet band are in contact with the inner surface of the forcing cone; the projectile and the charge are treated as a rigid body, and the charge quality is evenly coupled to the inner surface of the projectile in the form of mass points. As the rotating band is cut into the rifling, the internal element grid of the rotating band will be exposed to contact the inner surface of the forcing cone, so the element of the rotating band adopts a self-contact setting. figure 1 is a finite element grid model of the detailed structure of the starting section of the forcing cone, and figure 2 is an assembled projectile-firing mesh model. The number of model units is 1630594, and the number of nodes is 1811237.

![Figure 1. The finite element grid model of the forcing cone.](image)

![Figure 2. The FM model of projectile-barrel internation.](image)

2.2. Material model
The projectile undergoes elastoplastic deformation and damage during the engraving process, and eventually localized ductile fracture occurs, involving strain hardening, strain rate hardening, and temperature softening of the rotating band material. Johnson-Cook is suitable for describing most metal materials [13-14], So Johnson-Cook constitutive model and its failure constitutive model are used, and their expressions are:

\[
\sigma = [A + B\varepsilon^n][1 + C\ln \dot{\varepsilon}][1-\dot{T}^m]
\]  

(1)
\[
\bar{\varepsilon}_D^{pl} = [d_1 + d_2 \exp(-d_3 \eta)] \cdot [1 + d_4 \ln(\bar{\varepsilon}_0)] [1 + d_5 \dot{\varepsilon}]
\]

(2)

\[
\hat{T}^m = (T - T_r) / (T_m - T_r)
\]

(3)

Where \(\sigma\) and \(\varepsilon\) are material equivalent stress, plastic strain and plastic strain rate, respectively. Parameters \(A, B, C, m\) and \(n\) are material constants, \(\varepsilon_0\) is the material reference strain rate, \(\varepsilon^\text{eq}_D\) is the dimensionless temperature, \(T_r\) is reference temperature (room temperature), \(T_m\) is the material melting temperature; \(d_1 \sim d_5\) is material failure parameter, \(\dot{\varepsilon}_0\) is the relative strain rate, \(\bar{\varepsilon}_D^{pl}\) is the equivalent plastic strain at the beginning of material damage, \(\eta\) is the stress triaxiality. The material model for the gun barrel is taken from [15]. The material parameters used in the calculation are shown in the following table.

Table 1. Johnson-Cook material parameters of rotating band.

| A/MPa | B/MPa | n   | c   | D1  | D2  |
|-------|-------|-----|-----|-----|-----|
| 112   | 505   | 0.42 | 0.01 | 0.54 | 4.89 |
| D3    | D4    | D5  | m   |     |     |
| -3.03 | 0.014 | 1.2 | 1.68 |

Table 2. Johnson-Cook material parameters of gun steel.

| A/MPa | B/MPa | n   | c   | m   |
|-------|-------|-----|-----|-----|
| 1500  | 1600  | 0.25 | -0.0021 | 1.25 |

Table 3. Thermo-physical parameters of gun steel.

| Temp /°C | Conductivity K/W·m⁻¹·K⁻¹ | Specific heat CP /J·kg⁻¹·K⁻¹ | Thermal expansion α/ K⁻¹ |
|----------|---------------------------|-------------------------------|--------------------------|
| 20       | 33.8                      | 480.3                         | 1.21e⁻⁵                  |
| 300      | 37.9                      | 538.2                         | 1.21e⁻⁵                  |
| 600      | 36.8                      | 595.1                         | 1.21e⁻⁵                  |
| 900      | 30.5                      | 634.2                         | 1.21e⁻⁵                  |

Table 4. Thermo-physical parameters of rotating band.

| Temp /°C | Conductivity K/W·m⁻¹·K⁻¹ | Specific heat CP /J·kg⁻¹·K⁻¹ | Thermal expansion α/ K⁻¹ |
|----------|---------------------------|-------------------------------|--------------------------|
| 20       | 392                       | 391                           | 1.67e⁻⁵                  |
| 100      | 390                       | 397                           | 1.67e⁻⁵                  |
| 300      | 355                       | 407                           | 1.67e⁻⁵                  |
| 600      | 338                       | 420                           | 1.67e⁻⁵                  |
| 900      | 332                       | 428                           | 1.67e⁻⁵                  |

2.3. Boundary conditions and Loads

During the firing process, the high-temperature and high-pressure gas generated by the gunpowder combustion directly acts on the surface of the bore in the gun barrel. There is a temperature difference
between the high-temperature gunpowder gas in the barrel and the bore wall, so heat exchange must occur. Since the firing interval is relatively short during the continuous firing of the naval gun, it is assumed that before the projectile is squeezed in, the surface of the forcing cone has been heated by the gunpowder combustion. At this time, the gun barrel mainly receives three parts of heat: the first part is the heat that the gunpowder gas directly acts on the surface of the forcing cone in the form of forced convection heat transfer; The second part is the heat generated by the convective heat exchange of the cooling water on the outer wall surface. The third part is the continuous frictional heat between the emerging surface of rotating band and the surface of the gun barrel due to plastic deformation during the rotating band engraved into the rifling.

1 Initial conditions

\[ t = 0, \quad T = T_w, T_s \] is room temperature;

2 Inner and outer boundary conditions

\[ t > 0, \quad \text{The boundary condition of the inner surface of the gun barrel is:} \]

\[ \lambda_0 \frac{\partial T}{\partial r} \bigg|_{r=r_0} + h_g (T_g - T) \bigg|_{r=r_0} = 0 \quad (4) \]

\[ t > 0, \quad \text{The boundary condition of the outer surface of the gun barrel is:} \]

\[ \lambda_1 \frac{\partial T}{\partial r} \bigg|_{r=r_4} + h_e (T_e - T) \bigg|_{r=r_4} = 0 \quad (5) \]

Where \( h_g \) is the heat transfer coefficient between gunpowder gas and the inner surface of the gun barrel. \( h_e \) is the convective heat transfer coefficient of the surrounding air and the outer surface of the gun barrel, \( T_e \) is room temperature. During the projectile launch, the way in which the gunpowder gas flows axially along the gun barrel is a turbulent flow with a hot body. The prominent feature of this flow mode is the strong vortex motion. Therefore, the main form of heat exchange between the tube wall and gunpowder gas is forced convective heat transfer. To simplify the solution, it is assumed that there is only forced convective heat transfer. When the heat dissipation coefficient is obtained, appropriate corrections are made for radiative heat transfer. Heat release coefficient of gunpowder gas calculated according to similar theory [16]:

\[ N_u = f(L / d, R_s, P_r) = 0.023 \times R_e^{0.8} \times I_{e}^{0.4} \]

\[ = h(z, t) \cdot d / K_g(t) \quad (6) \]

Can be obtain from the above formula

\[ h_e(x,t) = 0.023 \times \frac{K_g(t)}{d} \times \left[ \frac{V(t) \rho_g(t) d}{\mu_g(t)} \right]^{0.8} \]

\[ \left[ \frac{C_{pg}(t)}{K_g(t)} \right]^{0.4} \times K_e \quad (7) \]

Where Reis reynolds number; Pris prandtl number; \( V \) g(t), \( K_g(t), \rho_g(t), \mu_g(t), C \) pg(t) are the flow rate, thermal conductivity, density, dynamic viscosity and specific heat of gunpowder gas; \( K_e \) is radiation correction factor.

In this study, the gravity load is directly loaded into the model as a constant force. The internal ballistic parameters of the positive charge are used, and the pressure is applied to all the active
surfaces at the rear of the rotating band in accordance with the pressure-time curve relationship of the bottom of the rotating band to simulate the powder gas. The effect on the projectile, as shown in figure 3. Without considering the impact of the squat sitting on the engraving process, and without considering the projectile jamming process, the initial position is that the projection of the rotating band is in close contact with the forcing cone to simulate the projectile engraving process.

![Figure 3. Curve relationship between bottom pressure and time.](image)

2.4. Friction model
During the engraving process, the rotating band material is first squeezed into the tapered forcing cone and then cut by the rifling. The contact pressure between the rotating band and the inner bore of the gun barrel is very large. At the end of the engraving, the projectile speed can reach a few Ten meters per second, so the friction between the rotating band and the tube has high speed and high contact pressure characteristics. Under high temperature, high pressure, and high speed environments, the friction coefficient between the rotating band and the forcing cone. Literature [17,18] pointed out that the friction coefficient between the rotating band and the gun barrel varies with the thermal physical properties of the material and the surface contact pressure. The rotating band width is related to the initial room temperature, and the relationship is shown in equation (9)

\[
f = u F_n
\]

\[
\mu = \frac{2 \lambda_p (T_m - T_0)}{P V \sqrt{\pi a_p H p/V}}
\]

Where \( H_p \) is the width of the rotating band, \( a_p \) is thermal diffusivity, \( P \) is contact pressure, \( V \) is slip speed, \( T_m \) is melting point temperature of the rotating band, \( T_0 \) is initial temperature, \( \lambda_p \) is thermal conductivity. In the ABAQUS commercial software, the subroutine VFRIC_COEF is used to change the friction coefficient between the rotating band and the forcing cone with temperature and pressure.

2.5. Wear Model
The wear calculation adopts the widely recognized Archhard model in practice [19,20]:

\[
dV = K \frac{dP \cdot dL}{H}
\]

Where, \( dV \) is the wear volume, \( dP \) is the normal pressure at the contact surface of the rotating band and the forcing cone, \( dL \) is the tangential image slip distance between the rotating band and the forcing cone, \( H \) is the hardness of the gun steel, \( K \) is the wear factor.
\[ dV, \ dP \ \text{and} \ dL \ \text{also expressed by:} \]
\[
\begin{align*}
    dV &= dWdA \\
    dP &= \sigma_u dA \\
    dL &= udt
\end{align*}
\]  
\[
(11)
\]
Where, \( dW \) is the wear depth, \( dA \) is the contact area; \( u \) is the relative slip speed, \( t \) is the slip time.
Substituting eq. (11) into eq.(10) can be obtained:
\[ dW = K \frac{\sigma u}{H} dt \]  
\[
(12)
\]
Its deformation formula is:
\[ W_j = \sum_{j=1}^{n} K \frac{\sigma_{ij} u_{ij}}{H} dt \]  
\[
(13)
\]
Equation (13) is used to calculate the amount of wear in a single engraving process. Where, \( W_j \) is the amount of wear at point \( i \) at time \( j \); \( T \), \( \sigma_{ij} \) and \( u_{ij} \) can be obtained directly from the results of the finite element simulation; \( n \) is the total number of steps in one simulation. Using Equation (3), the amount of wear that can be squeezed into the slope can be calculated.
Basic assumptions of the finite element simulation of the friction and wear of the forcing cone during the engraving process:
1) Due to the small amount of wear after a single shot, it is assumed that after each shot, the profile change of the forcing cone after shot will not affect the next shot.
2) It is assumed that the surface hardness of the gun barrel material remains constant under the continuous shooting environment.
In the process of projectiles being squeezed into the gun barrel, the friction and wear finite element simulation method of the forcing cone structure is mainly divided into two steps:
1) Simulate the sliding of the rotating band during the projectile's squeezed into the gun barrel, select the target node \( n \) from the finite element model, and use Python to extract the \( i \)th normal pressure and the slip speed of the node required to calculate the wear depth. In MATLAB, use equation (13) to calculate the wear amount after each calculation.
2) The temperature and residual stress of the node of the forcing cone obtained from the previous simulation are used as the initial conditions of the model for the next simulation. Regardless of the influence of the previous wear amount on the next one, repeat this 20 times and add the 20 times of wear to get the wear of the target position of the forcing cone after the projectile has been squeezed into the slope bore 20 times.

3. Test

3.1. Test equipment
Full-load ammunition of projectile for overload. The status is: standard launch charge;
- Black box: DRC276 data loggers; DRC277 data loggers. The trigger method of the black box is manual power-on trigger.

3.2. Test requirements
a) The Full-load ammunition of the launch overload test. The full bomb is maintained at high temperature (\(+50\ \)°C) for 48 hours. The black box is not insulated.
b) For each shot of the overload test projectile, the muzzle velocity is measured with a sky screen target, and 100% of the test projectile is recovered.
c) The test requires that the projectile is loaded into the bullet chain and then triggered by black box power-on. All firing actions must be completed within 5 minutes after triggering.
d) The DRC276 data logger is used in the black box for the launch overload test.
e) After firing the overload test projectile, disassemble and read the data.

Figure 4. Stress cloud diagram of the forcing cone in single shot.
Figure 5. Stress cloud diagram of the forcing cone in 10 consecutive firing shots.

Figure 6. Stress cloud diagram of the forcing cone in 20 consecutive firing shots.
Table 5. Factors in the table.

| Location        | Number | single shot | 10 consecutive firing shots | 20 consecutive firing shots |
|-----------------|--------|-------------|-----------------------------|-----------------------------|
|                 |        | $\sigma$ (MPa) | $u$ (mm/s) | Wear (mm) | $\sigma$ (MPa) | $u$ (mm/s) | Wear (mm) | $\sigma$ (MPa) | $u$ (mm/s) | Wear (mm) |
| Rifling lands   | Node 1 | 715 | 1545.18 | 0.022 | 814 | 1562.3 | 0.025 | 979 | 1583.9 | 0.031 |
|                 | Node 2 | 825 | 1634.14 | 0.026 | 913 | 1652 | 0.03 | 1013 | 1694.5 | 0.034 |
|                 | Node 3 | 681 | 2849.67 | 0.039 | 770 | 2855.2 | 0.044 | 912 | 2875.6 | 0.052 |
| Driving side    | Node 4 | 801 | 2324.62 | 0.037 | 984 | 2353.4 | 0.046 | 1120 | 2373.6 | 0.053 |
| No-driving side | Node 5 | 561 | 2324.62 | 0.026 | 628 | 2354.4 | 0.03 | 808 | 2373.6 | 0.038 |

4. Analysis of calculation results

The acceleration curve of the projectile engraving process during a single shot was obtained through numerical simulation calculation. By comparing with the experimental test, as shown in figure 7, the numerical calculation results are basically consistent with the test results. The validity of the established simulation model is verified to a certain extent. Based on it again, through numerical simulation calculations, the force state and wear law of the gun barrel bore under single-shot firing, 10 consecutive firing shots, and 20 consecutive firing shots were obtained.

![Comparison of acceleration curves](image)

4.1. Analysis of slope bore force

As shown in figure 4 to figure 6, in a single-shot shooting environment, the projectile is squeezed into the forcing cone under the action of gunpowder gas. At $t = 1.6 ms$, the rotating band has not been engraved at this time, and the rotating band is squeezed by the gun barrel. The elastoplastic deformation occurs, and the stress of the body bore is about 536 MPa; under the environment of 10 consecutive shots, the stress of the place is about 627.9 MPa; when the continuous shot is 20 times, the stress of the place is about 861.4 MPa.
With the increase of the bore pressure, the rotating band began to be engraved, and was accompanied by plastic damage and destruction. In the single-shot firing, 10 consecutive firings and 20 consecutive firing environments, at the time \( t = 1.65\)ms, the stress of the gun barrel is approximately 818Mpa, 936.7MPa, and 1278Mpa, respectively. At the time, \( t = 2.2\)ms, at this time, the front and rear rotating bands are engraved at the same time, and the stresses of the gun barrel are 921.4MPa, 1056MPa, and 1327MPa, respectively. In the case of continuous firing of 20 projectiles, the time is about 2.2ms, and the stress of the gun barrel reaches 1327MPa, which is not much different from the yield strength of the gun barrel material of 1500MPa.

4.2. Analysis of Slope Wear

In order to study the friction and abrasion of the barrel bore in the process of squeezing the elastic belt, as shown in figure 8. Based on the results of the finite element calculation, the contact pressures and slip speeds of the three element nodes (nodes 1, 2, 3) at the beginning of the rifling, the nodes 4 and 5 on both sides of the rifling turning side were extracted. Combine the formula (13) to calculate the amount of wear, as shown in table 5.

![Figure 8. Schematic diagram of node extraction location.](image)

As shown in table 5. It can be seen from table 5 that during 20 consecutive shots, the wear of node 1 on the slope bore increased by 24% compared to 10 consecutive shots; the wear of node 3 on the slope bore reached 0.052 mm, and the rifling was turned. The amount of wear on the side node 4 is 0.053mm, and the non-conductive side has a relatively small amount of wear due to the large contact pressure, which is 0.038mm.

5. Conclusion

The refined thermodynamic finite element model of missile-gun coupling was established, and a high-precision finite element mesh model of rifling with process chamfer was considered. The force of the slope and the wear of the slope were numerically calculated during the process of the projectile being squeezed into the slope. And got the following conclusions:

1) By comparing with the projectile acceleration curve obtained from experimental tests, the accuracy of the established high-precision finite element model is verified to be certain;

2) In the continuous shooting environment, the stress on the forcing cone gradually increases with the number of consecutive shots;

3) In continuous shooting environment, the wear of the slope bore gradually increases with the number of consecutive shots, and the wear on the transition between the forcing cone and the rifling guide is larger because the stress is more complex and is subject to the combined effect of compression force of the rotating band, friction and Thermal stress caused by temperature.

Since it takes too long to calculate the number of consecutive shots of 20 rounds, in future research, the finite element model will be further optimized to improve the calculation efficiency. At the same
time, as the number of shots increases, the amount of wear on the forcing cone will increase accordingly. Mesh shift during wear to obtain more accurate calculation results.

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