Study on Engraving Resistance Characteristic of Band Based on Different Structure Parameters of Rifling

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Abstract. The gun barrel working in complex environments is prone to damage, including the wear and ablation of the bore in the gun barrel. These changes cause changes in the rifling structure, which in turn affects the combustion law of gunpowder gas, which affects the pressure in the bore and changes the internal ballistics of the gun performance. This article takes a large caliber howitzer as the research object, considers the frictional force change during high-speed and high-pressure sliding, and also considers the energy conservation criterion during the engraving process. The initial ballistic equations are established during the initial movement period and Coupled solution with band engraving process. Considering the large deformation, high strain rate, temperature softening effect and cumulative damage effect, an explicit dynamic algorithm is used to compare the differences of the elastic band engraving process under different rifling structure parameters. The influence of different rifling structure parameters on the force state of the belt is analyzed. The influence of the main structural parameters of the engraving system on the belt engraving process is obtained. It provides a useful reference for the integrated analysis of the ammunition and the gun and the optimization of the barrel structure.

Key words: Rifling; band; engraving resistance; interior ballistics.

1. Introduction
Changes in the size and shape of the bore of the barrel under repeated cold and hot cycles and the physical and chemical effects of gunpowder gas are called wear. This wear is most serious at the beginning of the body line. When the barrel wear reaches a certain level, it will lose the required ballistic performance [1-2]. Fig. 1 is the curve of the maximum bore pressure and muzzle velocity of a large caliber artillery as a function of the bore wear. It can be seen that the ablation wear of the inner bore has an important influence on the maximum bore pressure and the initial velocity.

This article takes a large caliber howitzer as the research object, considers the frictional force change during high-speed and high-pressure sliding, and also considers the energy conservation criterion during the engraving process. The initial ballistic equations are established during the initial movement period and Coupled solution with band engraving process. Considering the large deformation, high strain rate, temperature softening effect and cumulative damage effect, an explicit dynamic algorithm is used to compare the differences of the elastic band engraving process under different rifling structure parameters.
The influence of different rifling structure parameters on the force state of the belt is analyzed. The influence of the main structural parameters of the engraving system on the belt engraving process is obtained. It provides a useful reference for the integrated analysis of the ammunition and the gun and the optimization of the barrel structure.

![Fig.1 Curve of maximum bore pressure and muzzle velocity of a large caliber artillery as a function of bore wear](image)

2. Theoretical basis

2.1. Inner Ballistic Equations

Taking the classical internal ballistic equation as the calculation model, the internal ballistic equation during the engraving period is as follows [3-4]:

\[
\begin{align*}
\psi_q &= \chi Z (1 + \lambda Z + \mu Z^2) \\
\frac{dZ}{dt} &= \frac{u_i}{e_i} \\
A_p (l_p + u dx) &= \frac{f \omega \psi_q}{\theta} - E_q
\end{align*}
\]

where:
\[
\begin{align*}
\left(0 - \frac{1}{\rho} - \frac{\Delta \rho - \alpha \Delta \psi_q}{\rho}ight)
\end{align*}
\]

Equation (2) is solved using the fourth-order Runge-Kutta method, and the initial value is set to the gas pressure in the charge chamber after the ignition charge is burned.

2.2. Force Analysis of Projectiles During Intra bore Motion

According to Newton's second law[5-6]:

\[
\begin{align*}
m \frac{dv}{dt} &= m \frac{d(v - v_i)}{dt} = Sp_q - R_i \\
I \frac{d\Omega}{dt} &= mp^2 \frac{d\Omega}{dt} = M_i
\end{align*}
\]

Assuming that the mass of the recoiled part is \( M \) and the quality of the charge is \( W \), then:

\[
m(v - v_i) + w v_o - M v_i = 0
\]
Among them, \( v_w \) is the average speed of the unburned pellets and gas, \( v_w = \frac{v}{2} - v_1 \), because \( v_1 \) can be calculated as:

\[
v_1 = \frac{m + w / 2}{M + m + w} \nu
\]

Therefore, the projectile equation of motion can be written as:

\[
\left( \frac{m + w / 2}{M + m + w} \right) m \frac{dv}{dt} = S_p \left( 1 - \frac{R}{S_p} \right)
\]

2.3. Johnson-Cook Constitutive Model

In the finite element model established in this paper, the constitutive model used for the band material is the Johnson-Cook model. The Johnson-Cook constitutive model is an empirical constitutive equation. Considering the effects of temperature and strain rate, Johnson-Cook material model consists of two parts.

Part I: Johnson-Cook plasticity model

In the Johnson-Cook plasticity model, Von Mises yield stress is a function of plastic strain, strain rate, and temperature [7].

\[
\sigma = (A + B \varepsilon_p^* \left[ 1 + C \ln \varepsilon_p^* \right] \left( 1 - T^\ast \right))
\]

\[
T^\ast = \frac{T - T_w}{T_m - T_w}
\]

\[
\varepsilon_p^* = \frac{\varepsilon_p}{\varepsilon_0}
\]

The temperature change caused by the adiabatic process is [8]:

\[
\Delta T = \int_{t_i}^{t_f} \frac{\sigma d \varepsilon_p}{pc_p}
\]

Part II: Johnson-Cook Fracture Failure Model

Johnson-Cook fracture failure model uses equivalent plastic failure strain \( \varepsilon_p^{KC} \) to define damage [9-10]:

\[
\varepsilon_p^{KC} = \left[ D_1 + D_2 \exp \left( D_3 \sigma^\ast \right) \right] \left[ 1 + D_4 \ln \varepsilon_p^* \right] \left( 1 + D_5 T^\ast \right)
\]

\( D_1 \sim D_5 \) is the failure parameter of the material; \( \sigma^\ast \) is the triaxiality of stress, that is, the ratio of hydrostatic stress \( \sigma_m \) to Von Mises equivalent stress \( \sigma_{eq} \):

\[
\sigma^\ast = \frac{\sigma_m}{\sigma_{eq}}
\]

3. Coupling model of band engraving process

3.1. Geometric Model

The geometric model of the band engraving process is shown in Fig. 2. The projectile starts from the position of the ramming and is pushed by the gas which acts on the bottom of the projectile. It overcomes the engraving resistance and advances along the axis of the barrel until the rear end of the band is completely engraved into the full groove.
3.2. Finite Element Model

The barrel and the projectile are meshed by the Solid164 hexahedron Lagrangian element, and the local mesh encryption was performed on the initial part of the groove. The band is calculated by the smooth particle fluid dynamics (SPH) algorithm. The finite element model of the barrel is shown in Fig. 3. The finite element model of the projectile is shown in Fig. 4. In the finite element model, there is no relative motion between the SPH particles and the non-grooved portion of the band. The point-to-face binding contact is used. The final finite element model of the band is shown in Fig. 5.

3.3. Material Parameters

In this simulation, an elasto plastic constitutive model is used. The material parameters are shown in Table 1.

| Physical quantity | Density $\rho$ (kg/m$^3$) | Elastic modulus $\nu$ (GPa) | Poisson’s ratio $\mu$ | Initial yield limit $\sigma_0$ (GPa) | Strength criterion |
|-------------------|---------------------------|-----------------------------|----------------------|----------------------------------|-------------------|
| Projectile        | 7820                      | 2.03                        | 0.3                  | 0.980                            | Von-Mises         |
| Barrel            | 7820                      | 2.03                        | 0.3                  | 1.030                            | Von-Mises         |

During the firing of the artillery, the belt is closely matched with the chamber bore, on the one hand, the gunpowder gas is sealed, on the other hand, the lateral force between the belt and the rifling gives the projectile a rotating movement. Since high strain rate deformation is usually accompanied by strain...
hardening, strain rate hardening, and temperature softening, the constitutive model usually associates stress with strain, strain rate, and temperature, which is usually expressed as:

\[ \sigma = f(\varepsilon, \dot{\varepsilon}, T) \]  

(14)

Where \( \sigma \) is stress, \( \varepsilon \) is strain, \( \dot{\varepsilon} \) is strain rate, \( T \) is temperature. Johnson and Cook proposed an empirical model that considers the effects of strain, strain rate, and temperature on stress:

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

(15)

The so-called regression analysis method is to find the optimal parameters such that:

\[ \text{min Error} = \sum \left( \sigma_{\text{exp}} - \sigma_{\text{predict}} \right)^2 \]  

(16)

Based on the impact test, this paper uses nonlinear fitting to obtain: \( A = 133 \text{ MPa} \), \( B = 324 \text{ MPa} \), \( n = 0.48 \), \( m = 1.21 \), \( C = 0.043 \), the above material properties are input into the finite element model for the calculation of the band engraving process.

3.4. Calculation Conditions

During the use of the barrel, there are two typical damages caused by ablation wear: the bore damage and the groove damage, characterized by the characteristic magnitude, including the length reduction of the bore and the shape change of the groove (the height of the land reduces and land is positive). In this case, the numerical simulation and analysis of the band engraving process in the three cases of these two typical injuries are carried out. The bore length of a large caliber howitzer calculated in this paper is 101 mm, while the length of the simulated wear bore is 120 mm; the height of the normal land is 1.27 mm, while the height of the simulated wear land is 1.1 mm, and the width of the normal land is 3.81 mm, while the width of the simulated wear land is 3.5 mm.

4. Result analysis

4.1. Numerical Calculation Results

In this paper, the band engraving process of a large-caliber howitzer with a length of bore 101 mm, a height of land 1.27 mm and a width of land 3.81 mm is calculated. The calculation results are shown in Fig. 6-10, and Fig. 6 shows the temperature field of band when the engraving is completed. With the temperature field distribution, it can be seen that the maximum temperature of the band is 189°C, which is much lower than the melting temperature of the band material of 1086°C. Fig. 7 shows the stress field distribution of the band when the engraving is completed. The maximum stress is 569 MPa, which exceeds the static yield stress of the band material of 123 MPa and the material undergoes yield deformation. Fig. 8 shows the plastic strain distribution of the band when the engraving is completed. When the engraving process is completed, the maximum plastic strain rate of the band is 1.528, and the strain rate of the back band is larger than that of the front band. Fig. 9 and Fig. 10 show the velocity and acceleration curves of the projectiles in the coupling calculation. Fig. 11 shows the curve of the engraving resistance in the process of engraving. There is a valley in the resistance curve; the law of the dynamic engraving resistance curve is quite different from that of the quasi-static model in the classical theory. The maximum engraving resistance is 88.9 KN, while the quasi-static is 86.68 KN. The value is slightly higher than the quasi-static engraving resistance.
4.2. Influence of Bore Wear on Engraving Resistance

The reduction of the length of the bore is used to simulate the wear of the barrel, the projectile and the height of the groove remain unchanged. Fig. 12 shows the change of the engraving resistance between the length of the bore of 101 mm and 120 mm respectively. It can be seen from the figure that the length of the bore becomes longer, the resistance of the projectile decreases, and the engraving pressure becomes smaller.
The reduction of the height of the land is used to simulate the wear of the barrel. Fig. 13 shows the change in the engraving resistance of the band along the length of the land of 1.27 mm and 1.1 mm respectively. After the groove defect, the height of the land reduces, in this case, the amount of overburden and the amount of force relatively reduces. The effect between the projectile and the barrel slows down, which can be understood that the maximum stress at the corresponding position of the bore becomes lower, the projectile is relatively easy to be engraved, and the maximum resistance of the band reduces from 88.9KN to 79.3KN.

The reduction of the width of the land is used to simulate the wear of the barrel on the side of the groove. Fig. 14 shows the comparison of the engraving resistance when the width of the land is 3.81mm and 3.5mm respectively. As can be seen from the figure, the width of the land becomes smaller, the initial resistance during the projectile engraving process reduces. The relatively increase of the width of the groove provides a larger material flow space for the band, and the band is easier to be engraved, and the maximum engraving resistance reduces to 77.8 KN.

5. Summary

In this paper, the classical internal ballistic equations are coupled with the band engraving process, and the coupled dynamics model of the band engraving process is established. The calculation of a large caliber howitzer band engraving process is carried out. On this basis, the difference in the engraving resistance of different bore structure is compared, and the following conclusions can be obtained:

1) The variation law of the dynamic engraving resistance of the band is quite different from the engraving resistance curve of the quasi-static model in the classical theory. The maximum engraving resistance is 88.9KN, while the quasi-static value is 86.68KN, and the dynamic engraving resistance value is slightly higher than the quasi-static engraving resistance.

2) The pressure on the bottom of the chamber is 168 MPa when the engraving process completes, which is much larger than 30 MPa in the classical internal ballistic theory. Therefore, the conventional engraving pressure assumes exists a large error.
(3) The heat generated by the adiabatic deformation of the belt during the engraving process is insufficient to melt the band material. The maximum temperature is 189°C, and the melting temperature of the material (1086°C) is not reached, so the band does not melt during the engraving process.

(4) The length of the bore becomes longer, the engraving resistance of the projectile decreases, and the engraving pressure becomes smaller; when the height of the land decreases, the amount of overburden and the amount of forcing relatively reduce during engraving process, the projectile is relatively easy to be engraved, the engraving resistance of the band reduces; the width of the land reduces, the initial resistance during the engraving process decrease, and the relative width of the groove increases, which provides a larger material flow space for the band, thereby it is easier to be engraved and the maximum engraving resistance decrease.

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