An investigation on plastic deformation of rotating band for large caliber gun projectile during engraving process

J H Guo1,2, X F Yao2, J M Qiao1, Y L Li1 and X D Zhang1.

1Northwest Institute of Mechanical and Electrical Engineering, No.5, Biyuan East Road, Xian Yang, Shaanxi province, 712099, People’s Republic of China, 2Department of Engineering Mechanics, Applied Mechanics Laboratory, Tsinghua University, Beijing, 100084, People’s Republic of China.

Email:guojunhang@163.com.

Abstract. The projectile engraving process of a large caliber gun is investigated by adiabatic process simulation based on smoothed particle hydrodynamics (SPH) and finite element method (FEM). The acceleration, velocity, displacement of the projectile are obtained, and the resistance force and moment applying on the projectile by the gun bore are also obtained. The resistance force varying with the travel of projectile is obtained and the curve reveal a peak in the particular position. At the beginning stage of the deformation, the force increased rapidly and then exhibits a slight transitional drop. The deformation process, equivalent stress, equivalent plastic strain, temperature and damage variable distribution of rotating band are obtained by numerical simulation. In order to visualize the simulation results, two kinds of post processing method are proposed. The frequency distribution of particles was get by particular variables, and the result showing that the maximum temperature of rotating band increment due to plastic deformation can be 150 degrees. Only few material can accumulated to the failure threshold, which indicates that large plastic deformation occurrences in rotating band while ductile fracture does no happen. The second method is to interpolate the field variable on a specified section by developing a program. The results show that the maximum equivalent stress is about 300MPa, the stress triaxility is less than zero, which indicates that most material under compression, and the maximum value of J3 related parameter is 0.5 located at rotating edge, which indicates material under shear loading, which agrees with the function of rotating band.

1. Introduction
The purpose of rifling is to impart to elongated projectiles the rotation necessary. As the projectile moves down the bore under the action of the powder gases, the lands cut through the rotating band, engraving it to conform the cross section of the bore, and causing rotation of the projectile. In the engraving process, the rotating band undergoes large plastic deformation. It is also the first progress in internal ballistics to produce suitable resistance which related to ignition of the propellant. So the design of the rotating band should be with some width to fulfill the rotation strength requirement, while with suitable resistance which is a comprehension result of structure and material and other factors.

The metal has been used widely during the past decade, while its plasticity and ductile fracture mechanism are still hot spots. As the rotating band under lager deformation and fracture is forbidden
in the bore, it is suitable to be studied with the theory of plasticity and ductile fracture. And by some numerical method like FEM, the engraving process of projectile can be simulated. There are two key points while such theories and methods are adopted, the feasibility to simulate and the precision we finally get.

When continuum element is used in simulation, the element may be excessively distortion and causes termination. Smoothed particle hydrodynamics (SPH) as a mesh-free method has been widely used [1, 2]. The solving region is split as particles in SPH method. Since nodal connectivity is not fixed, severe element distortion is avoided then it is very flexible and well suited to simulate large deformation problem. The dynamic simulation model of a projectile-barrel coupled system was established in [3, 4], based on the coupling of finite element method (FEM) and smoothed particle hydrodynamics (SPH) method. There are some researches on the plastic flow of the rotating band based on simulated for the engraving process of projectiles, only few of them focus on the failure of the material [5]. Whether fracture happens has not been well studied, the conclusions based on ductile fracture may not be accepted. Maybe the settings for ductile fracture in FEM only used to make the simulations carried out or feasible to simulate.

The material strength theory [6,7] is the basic knowledge to carry out these issues, which is connected with structure characterization, mechanical property, and its processing. The fracture theory is one of the most difficult problems in the science and has not been unified for its interdisciplinary, multi-scale and highly nonlinear [8]. The accurate fracture prediction of structures under loading has been of utmost interest in the scientific and engineering community over the past centuries, and is of practical importance in the design and optimization of processes and products. For ductile fracture, the materials experience large plastic deformation before total failure and exhibit high ductility and the fracture surface is relative macroscopic rough because of the void nucleation-growth-coalescence [10-12]. So, the investigation on the mechanical behavior of the voids in the metal is the basis of ductile fracture. Some approaches have been proposed to describe the voids behavior. It is well known that the mean stress and effective stress play important roles in ductile fracture, but the relation between the effective plastic strain at fracture and stress triaxiality is not generally monotonic [13]. Also, some experiments show that the ductility of metals is also influenced by the third stress invariant [13]. More and more tests show that the void evolution is influenced by shear deformation as well as tension [14-18]. Usually, the fracture mode of the sheet metal is always shear failure [18]. So the shear deformation or the third stress invariant also plays an important role in the fracture of metal.

However, the plastic deformation of rotating band for large caliber gun projectile during engraving process has not been well studied and reported on these aspects, such as the deformation process, equivalent stress, equivalent plastic strain, temperature and damage variable distribution. It is necessary to propose a model which can simulate engraving process with relative low calculation cost and acceptable precision, and can be used in other kind of guns.

2. Simulation model and boundary condition

The established model for the projectile-barrel system of 155mm gun is shown in figure 1. The rotating band is split into two parts and bonded in the interface. The outer part may undergo large deformation, so is model by SPH method, while the inner part can be modeled by finite elements and they were tied together. The diameter of the SPH node is about 0.574mm, so the groove (1.27mm depth and 6.33mm width) can be filled with at least 22 particles to ensure the solution accuracy. The mesh of projectile and barrel is also shown in figure 1, and the round and fillet in the rifle are ignored.
The effect of rotating band and rifles is a nonlinear problem for large deformation and other factors, so the Johnson-Cook yield constitutive [6] model (Eq.1) is chosen to describe the strain hardening, strain rate hardening, and temperature softening.

\[\sigma = (A + B\varepsilon^p)(1+C\ln\dot{\varepsilon})(1-T^n)\]  \hspace{1cm} (1)

\[T^* = \frac{T - T_r}{T_m - T_r}\]  \hspace{1cm} (2)

Here, \(\sigma\) is the flow stress, \(\varepsilon_p\) is the plastic strain, \(\dot{\varepsilon}\) is the strain rate, and \(T\) is the temperature, \(A, B, n, C, m\) are material constants, \(\varepsilon^* = \dot{\varepsilon}/\varepsilon_0\) is the dimensionless plastic strain rate, \(\varepsilon_0\) is the reference strain rate, \(T^* = (T - T_r)/(T_m - T_r)\) is the homologous temperature, \(T_r\) is the room temperature, \(T_m\) is the melt temperature.

The Eq.3 is used to calculate the temperature increment:
\[ \Delta T = \frac{\eta}{\rho c} \int_0^{\varepsilon'} \sigma d\varepsilon' \]  

(3)

Here, \( \rho \) is the density, \( c \) is the specific heat, \( \eta \) is the specified inelastic heat fraction coefficient. As the complex effect between rotating band and rifle and potential failure under large plastic deformation, so the Johnson-Cook [7] damage model (Eq.4) is adopted to calculate the damage. \( \varepsilon'_p \) is the equivalent plastic strain when fracture occurs.

\[ \varepsilon'_p = \left[ d_1 + d_2 \exp(-d_3 \eta) \right] \left[ 1 + d_4 \ln \varepsilon' \right] \left( 1 + d_5 T' \right) \]  

(4)

Here, \( \eta \) is the stress triaxiality, \( d_1 \sim d_5 \) are material constant. The damage of the material is computed by accumulation function as Eq.5,

\[ D = \sum \left( \Delta \varepsilon'_p / \varepsilon'_p \right) \]  

(5)

Here \( \Delta \varepsilon'_p \) is the increment of equivalent plastic strain, \( D \) is the damage variable, when \( D \geq 1 \), material failure occurs. Except for the rotating band, other structures are modeled as linear elastic material such as steel for barrel. In FEM model, the interaction between rotating band and barrel was modeled as friction behavior and a friction coefficient was reverse calibrated as 0.01.

The explicit adiabatic analysis which usually used in high-speed shocking process was chosen, for the engraving process completed in few milliseconds. The mechanical deformation causes heating but the event is so rapid that this heat has no time to diffuse through the material. The typical propellant pressure curve from interior ballistics is shown in figure 2, as a specific propellant condition, pressure was applied to the bottom of the projectile as loading curve.

**Figure 2.** The propellant pressure-time curve from interior ballistics.

### Simulation results and discussion

Under high propellant pressure, the projectile moves down the bore and the rotating band is engraved to conform the cross section of the bore. In the engraving process, the equivalent plastic strain distribution of rotating band obtained by simulation is shown in figure 3, at 1.7, 2.2, 2.8 millisecond respectively. The projectile is constructed with one rotating band of metal, slightly larger in diameter than the bore of the gun. The shape of rotating band is significantly formed under the effect of the lands and the equivalent plastic strain accumulates. At 2.8 milliseconds the shape of rotating band stabilized and the maximum equivalent plastic strain reaches 1.8.

**Figure 3.** The equivalent plastic strain distribution of rotating band in the engraving process.
The acceleration, velocity, travel of the projectile are also obtained by simulation as shown in figure 4. The projectile moves down the bore under high pressure of the propellant, with increasing acceleration, velocity and travel, which is slight difference with the interior ballistics results. The acceleration, velocity and travel reaches 80000m/s², 100m/s, 90mm when engraving process completed.

![Figure 4](image)

**Figure 4.** Acceleration, velocity, travel of the projectile obtained by simulation.

As rotating band engraved, the distribution of equivalent stress, equivalent plastic strain, temperature and damage variable are obtained by numerical simulation and shown in figure 5. The maximum equivalent stress can reach 570MPa, and the maximum equivalent plastic strain may reach 1.8, and the maximum temperature may reach 270℃, and the maximum damage variable may reach 1.0. But the distribution of such variables can not be well visualized because smooth particles always rendered as small balls. The distributions of these variables in the interior also can not be obtained as limiting function of software.
1) Equivalent stress; 2) Equivalent plastic strain; 3) Temperature; 4) Damage variable

**Figure 5.** Variable distribution of the engraved rotating band.

The axial resistance force and moment applied at rotating band obtained by simulation are shown in figure 6 and figure 7. The resistance force varying with time and travel of projectile are obtained and the curves reveal a peak in the particular position. At the beginning stage, travel less than 20mm or time before 2ms, the resistance force increased rapidly. Then travel between 20~40mm or time between 2~2.4ms, the resistance force reaches 400000N. Then travel between 40~60mm or time between 2~2.8ms, the resistance force decreased rapidly. In figure 7, the rotating moment obtained by simulation exhibits increasing trend with slightly fluctuation.

**Figure 6.** The resistance force of rotating band obtained by simulation.

**Figure 7.** The moment of rotating band obtained by simulation.
4. Post process for SPH region and Discussion

As the limitation of current post processor function, the results shown in Figure 3 and Figure 4 are not rendered as a field directly. A program was developed to get the node number, coordinates, equivalent stress, equivalent plastic strain, temperature and damage variable of the SPH particles from simulation output results and stored as a file. A program was developed to gather statistics of particle distribution by each particular variable as shown in figure 8.

As shown in figure 8, for the outer part of rotating band, the equivalent stress of most particles distribute between 200 to 500MPa. The stress triaxility of most particles under 1, which indicates that most material under compression loading while some material under tension. The Lode parameter of most particles distributed uniformly between -1 and 1, which indicates rotating and under shear loading. And this distribution agrees with the function of rotating band. The equivalent plastic strain, temperature and damage variable of most particles under 1.0, 150℃ and 0.2, respectively. Only few material can accumulated to the failure threshold, which indicates that large plastic deformation occurrences in rotating band while ductile fracture does no happen. Here, the Lode parameter defined as \( \cos(3\theta) = \frac{27J_3}{2\sigma_{eq}^3} \), \( J_3 \) is the third invariant of deviatoric stress tensor, \( \sigma_{eq} \) is the equivalent stress, \( \theta \) is the azimuth angle [8, 9].

![Figure 8](image1)

**Figure 8.** Variable distribution of the outer part of rotating band.

Figure 9 shows the SPH particle distribution of the engraved rotating band at a specified cross section region from simulation results, as the limitation of current post processor function, the shape of deformed structure or field variable of material region are not well rendered.

![Figure 9](image2)

**Figure 9.** SPH particle distribution of the engraved rotating band.
A program was developed to read result file obtaining the particle variable, and then interpolate the field variable by shape function on specified section then drawing the field. The plastic deformation of one quarter during engraving process are shown in figure 10, while the unit is MPa. The coordinate unit is mm. By this method, the variable distributions are rendered as a field. The rotation direction of projectile is clockwise in figure 10 and the axis unit is mm. The shape of rotating band can be well visualized by this method. It can be seen that at the rotating edge, the equivalent stress concentrates.

Figure 10. Equivalent stress distribution of the outer part of rotating band by interpolation (MPa).
By the mentioned program and method, the fields variables distributions of a portion of the outer part of rotating band at specified cross section are shown in figure 11. The coordinate unit is mm. By this program, the variable distributions are rendered as a field and suitable for post process. In this cross section, the maximum equivalent stress is about 300MPa locating at rotating edge. The distribution of equivalent stress is almost uniform in this cross section, as large compress plastic deformation and flow under the engraving process. The stress triaxility is less than zero, which indicates that most material under compression. The \( \omega \) parameter distributed between zero and 0.5, which indicates material under shear loading, which agrees with the function of rotating band. The value of stress triaxility minimizes at the rotating edge, while Lode parameter shows maximum value in the same area, as the shear stress dominates. The equivalent plastic strain, temperature and damage variable are about 0.4, 50℃ and 0.1 respectively. Here, the \( \omega \) parameter defined as

\[
\omega = 1 - \cos^2(3\theta) = 1 - \left(\frac{27J_2}{2\sigma_0^3}\right)^2,
\]

as ref [10-12]. And the maximum equivalent stress, Lode parameter, equivalent plastic strain, temperature and damage variable coincides in the same area indicating that material points at rotating edge under shear deformation and strain concentration.

![Field Variable distribution of the outer part of rotating band by interpolation.](image)

**Figure 11.** Field Variable distribution of the outer part of rotating band by interpolation.

5. Conclusions

The projectile engraving process of a 155mm gun at a given propellant pressure was investigated by numerical methods. The rotating band material was taken to be strain rate and temperature dependent. The rotating band was modeled by FEM and SPH methods. The resistance force as well as the movement of projectile were calculated. The distribution of equivalent stress, equivalent plastic strain, temperature as well as damage variable were obtained by numerical simulations. The statistics of equivalent stress, equivalent plastic strain, temperature as well as damage variable were calculated. And the distributions of these variables in a specified cross section was also interpolated by shape function. The conclusions list as follows:

1) The resistance force varying with the travel of projectile is obtained and the curve reveal a peak in the particular position. At the beginning stage of the deformation, the force increased rapidly and then exhibits a slight transitional drop.

2) The equivalent stress of rotating band can reach to 500MPa, while the stress triaxility under 1, which indicates that most material under compression loading while few material under tension loading. The Lode parameter of most particles distributed uniformly between -1 and 1, which indicates rotating and under shear loading.
3) The equivalent plastic strain, temperature and damage variable of most particles under 1.0, 150°C and 0.2, respectively. Only few material can accumulated to the failure threshold, which indicates that rotating band undergoes large plastic deformation while ductile fracture does no happen.

4) By developing a post process program, field variables distributions at a specified cross section were obtained. The distribution of equivalent stress is almost uniform in this cross section, as large compress plastic deformation and flow under the engraving process. The value of stress triaxility minimizes at the rotating edge, while Lode parameter shows maximum value in the same area, as the shear stress dominates. And the maximum equivalent stress, Lode parameter, equivalent plastic strain, temperature and damage variable coincides in the same area indicating that material points at rotating edge under shear deformation and strain concentration.

5) This method can also be used for other simulations in which smoothed particle hydrodynamics applied. The simulation model proposed in this paper can be used to optimize the structure and material of the rotating bands in other kind of guns.

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