Abstract

The interaction between large calibre artillery projectiles and the bore of the gun tube, it is made possible by a component called Rotating Band. This metallic annular shape component, deforms when it is forced against the forcing cone and the rifling of the bore.

This deformation will produce an obturation of the propellant chamber, which will generate a rotation. These are the main functions of a rotating band when considering real firing conditions. Knowing how this deformation occurs represents the main question when designing this type of equipments.

In this study, every physical phenomenon related to the quasi-static deformation will be approached considering three known manufacturing processes: extrusion, cut by shearing and cut by chip removal. With this analogy it will be possible to compute and replicate the behaviour of the rotating band, when it is forced in the bore.

As a conclusion to this study, it is possible to say that the cut mechanism has a great influence on the whole process. However, the extrusion contribution to the result cannot be excluded. Also, it was found that the dimension that governs the rifling force is the outside diameter of the rotating band.

Throughout this investigation, an analytical model was created, replicating the deformation mechanism of any rotating band, regardless of its dimension or composition.

Keywords


1. Introduction

When the goal is to design a projectile, one of the most relevant problem is the interaction between the projectile and the bore of the gun tube. For large calibre guns (Figure 1), this interaction is conducted by a metal annular shape component call Driving Band or Rotating Band.

Figure 1: Squematic view of a M107 grenade (Department of the Army, HEADQUARTERS, 1994)

In 2005, the FIREND® project started. The purpose of this project was to help fighting fires in high inaccessible places. The main goal was to create a 155 mm calibre grenade that, instead of carrying high explosives, would carry some kind of compound that would extinguish the flames, preventing their propagation and the consequent loss of lives (Calado, 2013) (Almeida, 2015).
Until now, only theoretical developments were made for this project, but nowadays the main goal is to develop a prototype. And before any prototype can be made, it is critical to understand how projectiles interact with the gun tube during internal ballistics phase.

When a solider starts the fire sequence, the gunpowder will start to burn, creating high temperatures and pressures that will be forced on the base of the projectile. Since the rotating band has a larger diameter than the gun tube, the projectile motion will only start when the pressure is high enough to overcome the band resistance. The rotating band is then deformed by the forcing cone and the rifling in the tube.

This rifling gives a rotation motion to the projectile itself, allowing a stable flight until it reaches the target and seals the chamber where the gunpowder is burning (Rheinmetall, 1982).

Not knowing the exact mechanism that deforms the rotating band, analytical models were created during this study. These models are based on three manufacturing processes: extrusion, cut by shearing and cut by chip removal. To validate the results originated from these analytical models, there will be a comparison with experimental data such as geometric layouts, dimensions and material behaviour. If both results (experimental and analytical) match, it could be said that, under those conditions, the model is valid.

Hartman & Stirbis (1974) were the first to use an approach that combine both analytical and experimental methods. Quasi-static push tests were conducted to a variety of 155 mm artillery shells. Those tests allowed to conclude that the rotating band pressure is more dependent upon the form and the mechanical proprieties of the band than upon the stiffness of the projectile (Hartman & Stirbis, 1973).

Montgomery (1984) presented a case study about the friction between band and tube. This friction affects the tube itself and, if it is not dealt with correctly, it decreases the life of the tube and its efficiency.

The life of the tube depends on the friction, being one of the most important subjects related to this topic. Andrews (2006) studied the relationship between the life of a tube and the charge used to propel the projectile. Using a variety of strain gauges along the exterior of the gun tube, Andrews (2006) could compute the pressure caused by the gas expansion and by the passing of the rotating band, for the different charges used.

In 2014, Wu et al. (2014a e 2014b) presented the most recent results about experimental tests conducted under quasi-static and dynamic loading conditions. Their goal was to understand the engraving process on different material bands, since this is of great importance from the viewpoint of optimal design, manufacturing, use, and maintenance of a gun projectile (Wu, et al., 2014b).

Still in 2014, Wu et al. (2014a) presented another investigation of great importance to the present article. With the bore tube and rotating band dimensions exactly described (Table 1), they obtained an experimental data that related the force necessary to move the projectile inside the bore of the tube (Wu, et al., 2014a).

<table>
<thead>
<tr>
<th>Test</th>
<th>$w_{CT}$</th>
<th>$D_{CT}$</th>
<th>$w_L$</th>
<th>$w_E$</th>
<th>$D_L$</th>
<th>$D_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-static</td>
<td>15</td>
<td>78.1</td>
<td>2.1</td>
<td>5.4</td>
<td>76.2</td>
<td>77.7</td>
</tr>
<tr>
<td>Dynamic</td>
<td>15</td>
<td>76.1</td>
<td>3</td>
<td>7</td>
<td>76.5</td>
<td>74.5</td>
</tr>
</tbody>
</table>

Table 1: Dimensions of the projectiles used for testing in millimetres (Wu, et al., 2014a)
If using the same dimensions and materials established in Wu et al. (2014a), the results obtained analytically matched with the ones on Figure 3, it is possible to validate the models created during this study.

2. Analytical Model Development

By creating an analogy with known manufacturing processes, it will be possible to compute the force needed to overcome the band resistance. In the end of the model development, the results will be compared to the ones obtained through experimental testing, confirming or not the validity of the model.

The base of the analytical models are three manufacturing processes that were chosen for being almost like the rifling that acts on the rotating band. Due to the difference of outside radius observed on the rotating band and gun barrel, there will be reduction caused by the forcing cone as the projectile advances. And then, when the rifling starts, the band will suffer a cut by rifling.

2.1 Extrusion

The reduction of the outside radius it is compared with an extrusion and the expression that rules the extrusion pressure is:

\[ P_e = \sigma_e \frac{1 + B}{B} \left( 1 - \left( \frac{h_A}{h_D} \right)^B \right) \]  

The previous expression gives the extrusion pressure by relating the geometric dimensions of the tube and band with the mechanical proprieties of the band material. The material is defined by the tensile strength, \( \sigma_e \), and the \( B \) parameter.

The tensile strength will be analysed on the following section and the \( B \) parameter is given by expression 2, that relate the friction coefficients (\( \mu_1 \) and \( \mu_2 \)) with the angle of the forcing cone, \( \alpha \).

\[ B = \frac{\mu_1 - \mu_2}{\tan \alpha} \]  

These friction coefficients represent the friction between the gun tube and with the projectile itself (\( \mu_1 \) and \( \mu_2 \) respectively).
2.2 Cut by Shearing

When the rifling begins, not all the volume of the band is cut. The volume that is cut instead of being extruded, can be associated to cut by shearing or by chip. The interior tube will assume the role of cutting tool.

![Figure 4: Simplified view of the transverse cross-section area of the tube where a) one set groove-land, b) groove, c) flanks and d) land](image)

When considering cut by shearing, the cut force is given by expression 3.

\[
F_{max} = R \times C \times \sigma_R \times pc \times w_{CT}
\]  

(3)

This expression has two corrective factors, \(R\) and \(C\). The first one is associated to the fact that this a non-horizontal cut. This condition is created by the forcing cone, and it will decrease the cutting force up to two thirds \((C=2/3)\). The second one is a material related constant, that depends on the material that is being cut. The cutting perimeter, "\(pc\)", depends on the geometry of each groove, and is given by expression 4:

\[
pc = (p_1 + p_2) \times N
\]  

(4)

Where:
- \(p_1 = p_2\) = land height [mm];
- \(N\) = number of grooves/lands;

The Ultimate Tensile Strength "\(\sigma_R\)", depends of the material that is being cut. In the following topic, the material related parameters will be analysed.

2.3 Cut by Chip Removal

On the other hand, when cutting by chip removal is assumed as the cut mechanism, the cutting force is given by the following expression:

\[
F_c = K_s \times e \times w_L
\]  

(5)

Where "\(w_L\)" and "\(e\)" represent the geometry of the cut, and "\(K_s\)" the material being cut. Being a material driven constant, "\(K_s\)" represents the specific energy, which can be found in numerous sources. The cut depth,"\(e\)", depends on the geometry of the cutting tool, being its maximum value given by:

\[
e_{max} = \frac{D_E - D_L}{2}
\]  

(6)

3. Parameters Definition

To ensure the quality of the results obtained through the analytical model, it is necessary to define materials behaviour and geometries. On the previous table (Table 1) it is possible to distinguish the geometries used by Wu et al. (2014a) on quasi-static and dynamic tests. But for the analytical model, it is necessary to define other detailed information about the geometry.

Figure 5 allows to understand the detailed information needed to develop each model. And Table 2 makes a comparison between the dimensions used on a 155 mm calibre projectile and the ones used by Wu et al. (2014a).

This detailed information is very useful, as it separates the rifling from the forcing cone. When the band starts its movement against the forcing cone, there will be a length that will not contain any rifling "\(w_A\)". After that, the rifling begins, creating a length where the band is being cut and extruded at the same time, "\(w_B\)".
When the rifling begins, due to the geometry, only a small part of the band volume is extruded until it reaches $h_{D_{min}}$. For this, a corrective factor, $J$, is applied to the extrusion pressure expression, lowering its original value.

![Schematic view of the cross-section area of the interaction between the band and the gun tube.](image)

**Figure 5:** Schematic view of the cross-section area of the interaction between the band and the gun tube.

Table 2: Description of the main geometric parameters used by the analytical models.

<table>
<thead>
<tr>
<th>Dimensional Parameters</th>
<th>“Firend”</th>
<th>“Bin Wu”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenght without rifling, $w_A$ [mm]</td>
<td>16.14</td>
<td>7.63</td>
</tr>
<tr>
<td>Lenght with rifling, $w_B$ [mm]</td>
<td>23.72</td>
<td>28.64</td>
</tr>
<tr>
<td>Lenght of rotating band, $w_{CT}$ [mm]</td>
<td>25.6</td>
<td>15</td>
</tr>
<tr>
<td>Maximum height, $h_A_{max}$ [mm]</td>
<td>4</td>
<td>2.55</td>
</tr>
<tr>
<td>Groove height, $h_{groove}$ [mm]</td>
<td>3.19</td>
<td>2.35</td>
</tr>
<tr>
<td>Minimum height, $h_{D_{min}}$ [mm]</td>
<td>1.995</td>
<td>1.6</td>
</tr>
<tr>
<td>Number of Grooves, N</td>
<td>48</td>
<td>32</td>
</tr>
<tr>
<td>Corrective Factor, $J$</td>
<td>0.4</td>
<td>0.28</td>
</tr>
</tbody>
</table>

With the established dimensions, the behaviour of the material represents a top priority. Considering the extrusion process, the material behaviour law used is based on a Ludwik-Hollomon equation. This assumption occurs because the elastic behaviour is not going to be considered (Rodrigues & Martins, 2010).

In this case, where the band is progressively deformed when in contact with the forcing cone, this equation assumes the following form:

$$\sigma_{unif} = \frac{K \varepsilon^n}{n + 1}$$  \hspace{1cm} (7)

Where “$K$” and “$n$” are two coefficients related to the band material, normally found on various tables. In this case, it is necessary to establish only three different materials, being the last one the material used on Wu et al. (2014a). The copper alloys are going to be used on the rotating band destined to the FIREND® project.

Table 3: Characterization of the materials used in the development of the extrusion model. Data obtained from (Kalpakjian & Schmid, 2008) and (Wu, et al., 2014a)

<table>
<thead>
<tr>
<th>Material</th>
<th>$K$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuZn30</td>
<td>895</td>
<td>0.49</td>
</tr>
<tr>
<td>CuZn15</td>
<td>580</td>
<td>0.34</td>
</tr>
<tr>
<td>Copper (T2)</td>
<td>1700</td>
<td>0.46</td>
</tr>
</tbody>
</table>

The Ultimate Tensile Strength, $\sigma_{UTS}$, present on expression 8, is defined by the Consideré Model and it is given by the following expression:

$$\sigma_R = Kn^n, \quad \varepsilon = n$$  \hspace{1cm} (8)

This relation allows to compute the $\sigma_R$, from Table 3. However, the previous value it is a true strength, and when it is corrected to a nominal strength it is computed with the following expression:

$$\sigma_{UTS} = K \left(\frac{n}{e}\right)^n$$  \hspace{1cm} (9)

Table 4: Comparison between nominal and true strength.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_R$ [MPa]</th>
<th>$\sigma_{UTS}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuZn30</td>
<td>630.9</td>
<td>386.5</td>
</tr>
<tr>
<td>CuZn15</td>
<td>402</td>
<td>286</td>
</tr>
<tr>
<td>Copper (T2)</td>
<td>1189.4</td>
<td>750.8</td>
</tr>
</tbody>
</table>

When the cut mechanism is compared with cut by chip removal, a specific energy must be defined. In the following table, it is possible to understand the difference between the different materials approached previously.
Table 5: Specific Energy (Schey, 1987).

<table>
<thead>
<tr>
<th>Material</th>
<th>$K_s$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1.2</td>
</tr>
<tr>
<td>Copper Alloys</td>
<td>0.8</td>
</tr>
</tbody>
</table>

4. Results

In this section, two main models are going to be analysed. These two models represent different rotating bands. The first one has the same dimensions and material as the ones used by Wu et al. (2014a), whose results are going to be confirmed using the same source. This model is named “Bin Wu”. The second model, represents an estimation about rotating bands destined to the FIREND® project, named “Firend”.

The main goal is to confirm that this model can replicate the deformation of real rotating bands, regardless of their dimensions and material. After having established this, the final model will be based on the following steps:

1. Compute the extrusion contribution by analysing the dimension of the tube and the band itself;
2. Compute the corrective factor due to the rifling origin that will give the final extrusion force;
3. Add the cut contribution.

4.1 Rotating Band “Bin Wu”

When it is all computed, it is necessary to choose between one of the cut mechanism. On Figure 6 it is possible two notice the differences induced by considering different cut mechanisms.

From the previous figures, it is possible to conclude that combining extrusion with cut by shearing, the force-displacement curve comes closer to the experimental curve. However, the values are considerably high. The following figure, shows the difference between the analytical and experimental data obtained.

From Figure 7 it is possible to say that the analytical curve, when considering cut by shearing, has a more stable evolution. The problem is the difference of the maximum force obtained. This difference can
be explained by the simplifications made along this investigation. These simplifications are based on:

- Simplified geometrical shape of the analytical band;
- Analytical considerations regarding the cut mechanism.

4.2 Geometric Parameters Influence

There are many parameters on the analytical model that can be changed. This alteration will cause a big difference on the results obtained. For instance, if the width and the outside diameter are increased, the total force needed to overcome the resistance of the band rises significantly.

This new shape will cause a 50% reduction on the extrusion forces by lowering the volume that is going to be extruded. This modification will also reduce the length of the rotating band “$w_{CT}$” (found on the expression 3) being cut, by allowing that some portion of the band enters directly in to the bore without ever touching the rifling. This allows to fix the grenade on the tube when it has an elevation, stopping the grenade from falling on the ground before the chamber is closed.

The maximum cut perimeter has been computed until now using the cut geometry, but if there are any gaps between the band and the bottom of the groove, this parameter will decrease. This is a possible assumption because any gases trying to escape will be stopped by the extrusion that is happening before the cut.

Considering a 50% decrease of the extrusion force due to the convectional shape, a 20% decrease of the “$p_C$” used on expression 3 due to possible gaps and a 5 mm reduction on the length of the band that is being cut, it is possible to obtain a new evolution (Figure 10).

It is possible to conclude that the new curve (blue line) and the experimental curve (red line) are more alike than before and very similar if considered the maximum force obtained.
4.3 Rotating Band to the FIREND Project

When considering a rotating band for a 155 mm calibre grenade, the dimensions of the band are not the only ones that change. The geometric definition of the tube’s interior is a lot different. Those differences will change the results obtained but not the methodology used by the analytical models.

Since there are no experimental data capable to validate the results, this next figure represents only an estimation of the force needed to deform a rotating band from a 155 mm calibre projectile.

Considering the results obtained, it is necessary to remove the simplifications mentioned before, so the results can be closer to the reality of a quasi-static deformation.

5. Conclusions

By the end of this investigation, it is possible to confirm its contribution to the knowledge of the quasi-static deformation of rotating bands.

It was found that the total deformation could be approximated to three known manufacturing processes: extrusion, cut by shearing and cut by chip removal. In the end, combining the extrusion with cut by shearing represent the closest approximation to the experimental results given by Wu et al. (2014a).

However, this approximation only appears when the simplifications are removed from the analytical computations. Those simplifications were based on the form of the band and on the way the band is cut. With those simplifications, the values obtained are much higher and do not correspond to any experimental data. The alteration of the form reduces the volume of the band that is extruded and the length that is cut. This will cause a reduction on the extrusion and cut force, respectively.

Comparing Figures 7 and 10, it is clear the difference caused by those simplifications. A 170 kN reduction on the maximum force can be observed.

However, there are many similarities observed since the first comparison with the experimental data (Figure 7). The maximum force appears in the same instance of the displacement, and the experimental curve (red line) has numerous inflexion points that correspond to the contact with the rifling. Those similarities confirm the success of this investigation.
6. References

Almeida, L. (2015). Stress analysis and design of a 155 mm projectile shell to be used in fire fighting. Tese de Mestrado, Instituto Superior Técnico, Departamento de Engenharia Mecânica, Lisboa.


